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BUILDING COMMISSIONING: INNOVATION TO PRACTICE TECHNICAL REPORT

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Preface

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

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For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-654-4878.

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Abstract

Building Commissioning: Innovation to Practice was a multi-state collaborative project co-funded by a grant through the U.S. Department of Energy State Technologies Advancement Collaborative. Nearly half of this project's funding was provided by the Public Interest Energy Research (PIER) Program, managed by the California Energy Commission. The objectives of the *Building Commissioning: Innovation to Practice* project were to develop and introduce the market application of innovative and practical functional performance testing, diagnostic tools, and training for commissioning providers and building owners.

This project involved six elements designed to standardize and streamline building commissioning approaches through new tools and technology:

- Element 1: Functional Testing Guide on-line resource development
- Element 2: Functional testing guidance document development
- Element 3: Advanced hands-on training for new and existing building commissioning
- Element 4: Functional Testing Checklist Tool development
- Element 5: Functional Test Data Analysis Tool development
- Element 6: Advanced Building Commissioning Analysis Tool development

The feedback obtained from initial deployments was used to improve the commissioning tools and training, obtain improved information about the benefits and costs of adopting these commissioning tools, and expand the market awareness of the benefits of commissioning.

Keywords: Commissioning, functional testing, commissioning provider, training, diagnostic tools, building operator, FT Guide, fault detection and diagnostics, FDD, HVAC, whole building energy, simulation, calibration, commissioning tools, retrocommissioning

Executive Summary

Introduction:

The *Building Commissioning: Innovation to Practice* project was a multi-state collaborative project funded by a grant through the United States Department of Energy State Technologies Advancement Collaborative program sponsored by the National Association of State Energy Offices. Nearly half of this project's funding was provided by the Public Interest Energy Research Program and the following partner states represented in the project – California, New York, Texas, Oregon, Washington, Idaho, Montana, Nebraska, and Iowa.

Purpose:

The project set out to streamline building commissioning practices by addressing two widely recognized barriers to the adoption: uncertainty about the cost savings and other benefits; and the need for tools and technologies that standardize and simplify commissioning approaches and reduce implementation costs. According to the Building Commissioning Association, building commissioning provides documented confirmation that building systems (such as heating ventilation, and air-conditioning. Electrical, and lighting systems) function according to criteria set forth in the project documents to satisfy the owner's operational needs. Both barriers require development of straightforward, cost-effective tools and techniques to help standardize and simplify commissioning approaches and reduce costs, which will help convince owners nationwide to commission their buildings and enable them to do so more cost-effectively.

Project Objectives:

The *Building Commissioning: Innovation to Practice* project was to develop and introduce the market application of innovative yet practical functional performance testing and diagnostic tools and training to commissioning providers and building owners in the partnering states in this project.

This project involved six elements that were directed at overcoming owner and industry barriers to the adoption of building commissioning.

- **Element 1**: **Enhance the Functional Testing Guide for Air Handling Systems.** Project Element 1 was to produce an enhanced on-line version of the Functional Testing Guide with improved functionality and presentation to increase the use of this resource.
- **Element 2**: **Develop Additional Functional Tests for Functional Testing Guide.** Project Element 2 was to enhance the Functional Testing Guide with additional content beyond Air Handling Systems to help commissioning providers develop high-quality functional tests more quickly.
- **Element 3**: **Develop and Present Commissioning Training Using Functional Testing Guide.** Project Element 3 was to develop and present training for commissioning providers that focused on developing and implementing functional tests using the

Functional Testing Guide and identifying typical energy-saving opportunities commonly found through the retrocommissioning process.

- **Element 4: Develop and Deploy Functional Testing Checklist Tool.** Project Element 4 was to develop and test a tool that can be used by commissioning providers as a resource to develop high-quality functional tests more quickly – improving the cost-effectiveness of commissioning.
- **Element 5: Develop and Deploy Functional Test Data Analysis Tool.** Project Element 5 was to develop and pilot test an automated tool that analyzes and displays data produced by functional performance tests for common heating, ventilating and air-conditioning components to identify significant faults.
- **Element 6: Develop and Demonstrate Automated Building Commissioning Analysis Tool.** Project Element 6 was to develop and demonstrate an advanced prototype of the Automated Building Commissioning Analysis Tool, a diagnostic tool that detects deviations from expected building energy use, to an advanced prototype stage and demonstrate its effectiveness in pilot test sites.

Project Outcomes:

Each project element resulted in the development and initial market application of innovative and practical functional performance testing and diagnostic tools and training for commissioning providers and building owners in at least two of the following participating states: California, New York, Texas, Nebraska, Iowa, Oregon, Washington, Idaho, and Montana.

<u>Functional Testing Guide</u>

- <u>Element 1: Enhance the Functional Testing Guide for Air Handling Systems (Functional Testing Guide)</u>

  Input from commissioning providers was solicited on how the Functional Testing Guide is used in practice, the extent to which the guide streamlined test writing and improved the quality of the tests, and how educational information was used to troubleshoot problems. They were also asked to recommend improvements. Portland Energy Conservation, Inc., addressed the recommendations of the pilot participants through revisions to the Functional Testing Guide's content, functionality, and presentation. The functional testing field tips sections of each module were enhanced to clearly describe key commissioning test requirements, key preparations and cautions, and the time required to test. Activity to enhance the functionality and presentation of the Functional Testing Guide resulted in a conversion to a Web-based format of the original guide and content recently developed under a separate United States Department of Energy-funded project. This effort included a variety of navigation and design enhancements to facilitate use of the guide by commissioning providers with different levels of experience. The newly enhanced Functional Testing Guide is available at www.ftguide.org.

- Element 2: Develop Additional Functional Tests for Functional Testing Guide

  Prior reviewer feedback on the Functional Testing Guide stressed the importance of developing additional functional tests that were not publicly available. Results from the Functional Testing Guide pilot surveys conducted in Element 1 helped identify and prioritize additional functional test forms that could be added to the Functional Testing Guide. The prioritized list of test forms was reviewed by a team of experienced commissioning providers from the states participating in the project. When using a resource such as the Functional Testing Guide, commissioning provider feedback pointed to the need for guidance on what makes an effective functional test rather than creating test forms for which commissioning providers often have their own style. In response to this feedback, Portland Energy Conservation, Inc., developed testing guidance documents for 14 of the prioritized tests. The testing guidance documents describe the steps and potential issues that may arise during functional testing. Commissioning providers may use the testing guidance to expand and improve upon their existing forms. The new testing guidance documents were piloted, and the general consensus from the pilot participants was that the testing guidance was a useful way to improve their tests or build new ones. The testing guidance documents were incorporated into the new final version of the Functional Testing Guide.

- Element 3: Develop and Present Commissioning Training Using Functional Testing Guide

  Portland Energy Conservation, Inc., developed a one-day interactive training curriculum to teach test providers how the Functional Testing Guide can be useful in streamlining their functional testing process. Portland Energy Conservation, Inc., engineers presented the one-day Functional Testing Guide training workshops in California, Iowa, Oregon, Washington, Idaho, and Montana. In the workshop, the instructor led the audience through the Functional Testing Guide’s features and uses, then guided the group in developing and conducting a functional test at the training site. Portland Energy Conservation, Inc., also developed a four-day advanced hands-on training curriculum that covered the retrocommissioning process and technical methods for identifying opportunities (including historical operating information, drawings and specifications, visible indicators, utility consumption, data logging and trending, system flow diagrams, and targeted testing). The training also included instruction on how the Functional Testing Guide can be useful in streamlining testing. Portland Energy Conservation, Inc., engineers presented two of these advanced hands-on commissioning training courses in New York and one in California.

- Element 4: Develop and Deploy Functional Testing Checklist Tool

  Portland Energy Conservation, Inc., developed a Functional Testing Checklist Tool (Checklist Tool) that provides commissioning providers with a quick way to evaluate a test. The Checklist Tool can also be used as a portal into the Functional Testing Guide for specific testing information. The Checklist Tool contains checklists covering 17 functional tests for various systems and components, including air handling, chillers, condensers, boilers, cooling towers, and pumping. Each item on a checklist has a link into the Functional Testing Guide – directing the user to background information on why specific elements of a test are important and providing additional information needed for testing. As with the other project elements, the checklists were piloted with the group of commissioning providers and feedback was used to make revisions and enhancements.

- <u>Element 5: Develop and Deploy Functional Test Data Analysis Tool</u>

  Lawrence Berkeley National Laboratory developed a prototype of the Functional Test Data Analysis Tool (Functional Testing Data Analysis Tool). This tool uses a library of data analysis routines to analyze functional test data obtained through a series of prescribed test steps. The tool assesses component performance and identifies the likely causes of failure. The tool's user interface allows manual entry of test measurements and shows the measured performance versus the expected performance, highlighting significant differences that led to the component failing the test. The tool will be useful to commissioning providers conducting functional tests in both new and existing buildings, as well as to building owners and operators that conduct routine tests periodically to check their heating, ventilating, and air-conditioning system performance. Staff from the Iowa Energy Center with experience in the development and testing of fault detection and diagnostic tools performed the first beta test of the tool, and commissioning providers in California and New York piloted the tool in actual building applications.

- <u>Element 6: Develop and Demonstrate Automated Building Commissioning Analysis Tool</u>

  Texas A&M University and the University of Nebraska developed and demonstrated a prototype version of the Automated Building Commissioning Analysis Tool by building upon previous work funded by the California Energy Commission's Public Interest Energy Research Program. The Automated Building Commissioning Analysis Tool provides automated detection of significant building energy performance degradation using a simplified building simulation platform and projects the economic benefits from correcting degradation of the building systems. The types of faults that are most likely to avoid detection in buildings today are the types that are difficult to detect on the daily level but have a significant impact when allowed to continue for a period of weeks, months, or years. The primary fault detection metric established in the Automated Building Commissioning Analysis Tool is the cumulative energy difference plot, which takes the daily difference between the measured and simulated consumption of the previous day, and adds it to the current day. Providing this in cost form is expected to compel users to take action when faults are detected. On-line testing of the Automated

Building Commissioning Analysis Tool detected three significant consumption deviations that otherwise went undetected by building personnel.

Conclusions:

The *Building Commissioning: Innovation to Practice* project set out to streamline commissioning practices. The Functional Testing Guide is a resource that helps commissioning providers develop well-written functional tests more quickly – improving the cost-effectiveness of achieving a high-quality commissioning project. Similarly, the development of semi-automated tools that support the process of functional testing (as with the Data Analysis Tool) and improve the persistence of commissioning activities (Automated Building Commissioning Analysis Tool) will also increase commissioning benefits and reduce costs in the long term. Helping train and expand the infrastructure of commissioning providers while improving the delivery efficiency of experienced providers will improve the cost-effectiveness of commissioning, leading to greater market penetration to achieve energy savings.

Recommendations:

<u>Functional Testing Guide</u>

Based on feedback from peer reviewers and Portland Energy Conservation, Inc.'s, communication with commissioning providers, the following projects are recommended for future research to further support the commissioning industry:

- *Add modules to Functional Testing Guide*: A few common systems are not covered in the FT Guide, most notably steam systems and electrical systems. Technical content could be developed for these systems that address key commissioning tasks and common problems.
- *Develop reference guide material for modules*: The level of detail for each newly developed module (boiler systems, chiller systems, condenser systems, pumping systems) should be further developed to a level of detail similar to the Air Handling System Reference Guide.
- *Develop additional tests*: In key areas, develop additional testing guidance documents and add them to the Functional Testing Guide Test Directory.
- *Provide specialized commissioning training opportunities*: Additional training is needed to continue to expand and improve the skills of the commissioning provider pool as industry growth outpaces supply of qualified providers. To support this growth in training needs, it is necessary to also provide specialized training for instructors to help expand the instructor pool ("train the trainer") .

Functional Testing Data Analysis Tool

Commissioning providers that evaluated the Functional Testing Data Analysis Tool felt that the tool would be beneficial in improving heating, ventilating, and air-conditioning system performance if it were further developed. The following research initiatives are recommended:

- Implement improvements to the operation and interface of the tool.
- Extend the tool to include other components or component variations to provide more comprehensive treatment of the range of equipment types and configurations encountered in air handling units.
- Extend the scope of the tool to include closed-loop testing in order to test some control functions and reduce the need for controls technician assistance in testing.
- Develop a training tool for functional testing and troubleshooting based on the tool.

Automated Building Commissioning Analysis Tool

Insight into the true marketability of the Automated Building Commissioning Analysis Tool tool will require a larger scale (10+ building) implementation over the next two years. Installing the Automated Building Commissioning Analysis Tool before commissioning activities in these buildings appears to be a good way of tracking savings due to commissioning measures, and it also provides an opportunity to reverse test the diagnostic method of the tool. Training additional expert users of the tool and developing supporting software, tools, and detailed documentation to simplify the calibration procedure will help in the dissemination of the tool among multiple users and obtain an even greater level of detail and diversity in feedback.

Several developmental issues, particularly in the areas of improving data transfer and storage and further testing of the fault detection and diagnostic methods, should be addressed early in continued research. The experiences of new building implementations should also lend to continued development and additional functionality built into the Automated Building Commissioning Analysis Tool simulation model.

Benefits to California and Other Participating States:

Initial deployments of the resources and tools developed through the project benefited California as well as other participating states in numerous ways, as listed below by project element.

Functional Testing Guide

The enhanced Functional Testing Guide is now a publicly available Internet resource that exposes commissioning providers to practical information about system performance and energy efficiency opportunities and helps to streamline functional testing efforts through the use of testing guidance documents, sample functional tests and the Checklist Tool. A link to the Functional Testing Guide on-line resource has been placed on the California Commissioning Collaborative website. Additionally, many commissioning providers, facility managers, and mechanical engineers benefited from attending the building commissioning training courses offered through the project. Through hands-on activities and instruction, training attendees developed an understanding of the retrocommissioning process, learned technical methods for identifying opportunities, and developed skills in writing and performing functional testing. The training courses also helped to expand the market awareness of the benefits of commissioning in the states in which they were held (New York, California, Oregon, Washington, Iowa, and Idaho).

Functional Testing Data Analysis Tool

Widespread deployment of the Functional Testing Data Analysis Tool will enable the energy performance and controllability of air handling units to be tested more easily. The improved performance made possible by this testing will benefit building owners through lower utility bills, building occupants through improved comfort control, and local and global environments through reduced emission of pollutants. The development of the prototype tool is a starting point for a more comprehensive tool that will enable greater performance benefits by promoting the thorough functional testing of building systems.

Automated Building Commissioning Analysis Tool

With wide scale deployment of a simplified tool such as the Automated Building Commissioning Analysis Tool to commissioning service providers, building owners, and engineers, the long-term persistence of savings from building commissioning can be realized with continuous energy tracking. The Automated Building Commissioning Analysis Tool may also aid in wider acceptance of building commissioning services by presenting building owners with a tool to monitor continued savings. With persistence of savings as a key issue in the acceptance and advancement of the commissioning practice, tools that promote and improve persistence are important to the industry.

Chapter 1.0 Introduction

The *Building Commissioning: Innovation to Practice* project set out to streamline building commissioning practices by addressing two widely recognized barriers to the adoption of commissioning: (1) uncertainty about the cost savings and other benefits; and (2) the need for tools and technologies that standardize and simplify commissioning approaches and reduce implementation costs. The first barrier—an owner's uncertainty about the benefits of commissioning and its perceived high first cost—can prevent building owners from even considering commissioning. The lack of standardized commissioning processes contributes to this problem. Even an owner who is convinced of the value of commissioning has difficulty purchasing poorly defined services of unpredictable scope.

The second barrier to widespread uptake of commissioning is the lack of commissioning standards and commissioning tools. One critical phase of the commissioning process faced by experienced providers and new entrants is the need to assess and diagnose equipment operation, system performance, and functional integration in the field—which is accomplished through functional testing and diagnostics at all three levels. Although functional testing is critical, it is not standardized across the commissioning industry, nor is it well understood or properly implemented by most large commercial building operators or facility managers. Similarly, diagnostic tools and techniques for building operators to continually monitor and assess HVAC system performance are not widely used, in part because existing tools appear to be too complicated and/or expensive to integrate into existing building maintenance practices.

Both barriers require development of straightforward, cost-effective tools and techniques to help standardize and simplify commissioning approaches and reduce costs—which will convince owners nationwide to commission their buildings and enable them to do so more cost-effectively.

The project's six elements are directed at overcoming owner and industry barriers to the adoption of building commissioning with the development and initial market application of innovative yet practical functional performance testing and diagnostic tools and training for commissioning providers and building owners. The state partners in this project are California, New York, Texas, Nebraska, Iowa, Oregon, Washington, Idaho, and Montana. Each of these states has been actively involved in developing commissioning infrastructure and practices for over a decade. They represent the areas of the country with the largest commitment and greatest experience in making commissioning commonplace, which is evident by their long track records of sustained commitment to commissioning research and program implementation.

1.1. Background

<u>FT Guide/ Additional Functional Tests/ Checklist Tool</u>:

The FT Guide project elements 1, 2, 3, and 4 of the *Building Commissioning: Innovation to Practice* project build from the original *Functional Testing Guide for Air Handling Systems* that was based on Pacific Gas & Electric's Commissioning Test Protocol Library (CTPL), a clearinghouse of tests which were cataloged and evaluated and made available in a database format. Non-copyrighted tests are publicly available for download. The *Functional Testing Guide for Air Handling Systems* complemented this source of sample test procedures by providing guidance in developing and executing these tests. The guide provides information on the purpose of performing the tests, cautions when performing the tests, and typical problems uncovered by the tests and how to address them.

This initial version of the FT Guide was created through a cost-share between the California Energy Commission's Public Interest Energy Research (PIER) program and the U.S. Department of Energy (U.S. DOE). LBNL was in charge of project oversight and for developing navigation functionality, while the technical content was developed by PECI. The FT Guide was developed in a format of hyperlinked Word documents that included a program macro-generated Document Access Panel where the user could directly access test procedures.

Starting before the *Building Commissioning: Innovation to Practice* project, and providing information to build from and leverage, a U.S. DOE-funded project, *Extension of the Functional Test Guide,* was initiated in 2004 to determine the most useful means of building upon this resource through surveys, then implementing those recommendations. The survey results showed that many commissioning providers had copies of the FT Guide but had not used it, which contributed to the direction of the enhancement element of this project. The *Extension of the FT Guide* project also developed additional content for the guide and expanded it beyond air handling systems to include chillers, condensers, boilers, and pumping – enabling the work under this project to address the enhancement and piloting of a more developed resource.

One additional U.S. DOE-funded project, Annex 47, simultaneously developed functional tests for low-energy buildings. These were incorporated into the FT Guide along with the testing documents developed and piloted under the *Building Commissioning: Innovation to Practice* project. A diagram illustrating the current format of the FT Guide is provided in Figure 1.

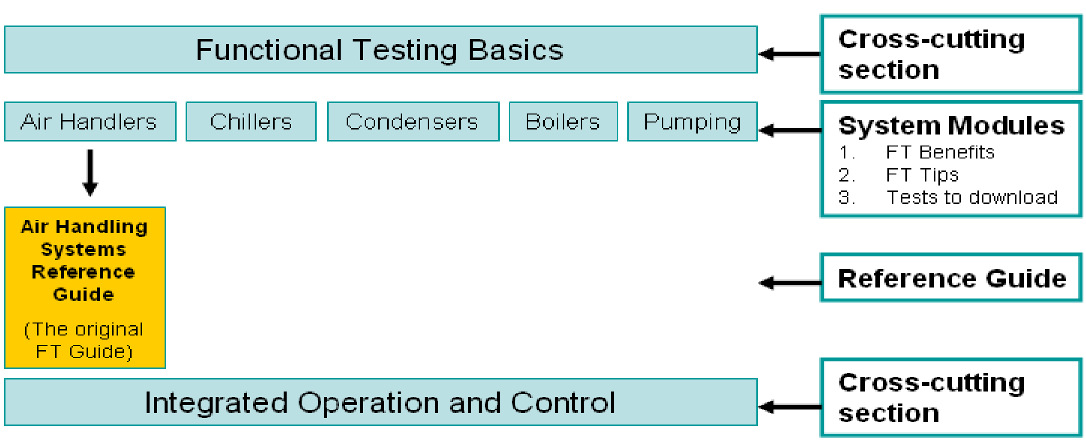


Figure 1. FT Guide Online Format

Functional Test Data Analysis Tool:

The FT Data Analysis Tool takes analysis methods first developed for automated diagnostic tools and applies them to the analysis of the results of manually performed functional tests. The methods were originally developed in the High Performance Commercial Building Systems Program, funded by the California Energy Commission and U.S. DOE. By combining measurements from temporary instrumentation with measurements from the building control system, the FT Data Analysis Tool has an advantage over other tools that obtain their measurements strictly from the building control system.

ABCAT:

Despite all of the recent advancements in building technology, tools that support users in ensuring energy optimization and efficiency of building HVAC systems have not gained significant acceptance in the marketplace.

The past approaches to whole building level fault detection and diagnostics (FDD) have primarily relied on black-box or empirical models that require extensive training data to configure their prediction models. The use of detailed first principles or physical models (e.g. DOE-2, EnergyPlus) does not provide a viable alternative, since they tend to be over-parameterized and can often require significant experience and time to provide an accurate representation of the building. *Calibrating* or tuning these detailed simulation models has also be shown to require significant effort (Bronson et al. 1992; Haberl and Bou-Saada 1998). Simplifying these physical models, as is done with ASHRAE's Simplified Energy Analysis Procedure (SEAP) (Knebel 1983), has repeatedly been shown to provide reasonable accuracy (Katipamula and Claridge 1992; Liu and Claridge 1998) without excessive complexity. Such a model has been shown to be a manageable model for work in semi-real-time fashion.

The development of the ABCAT builds on previous work funded by the California Energy Commission's PIER High Performance Commercial Buildings Program (HPCBS) in the areas of Simulation Assisted Commissioning and Calibrated Simulations. The ABCAT is to make new and unique whole building fault detection tests and passive analysis and tracking techniques available to advanced commissioning providers.

A manual systematic approach to calibrating first principles models with the procedural manual of Claridge et al. (2003) has helped to minimize the expertise needed to calibrate a model. The approach, with the use of energy signatures, assists the user in clearly understanding the impact of various changes to the simulation parameters, as well as to help target the changes required for improved model accuracy. Using this procedure with a simplified first principles model provides a simplified alternative for predicting building energy consumption, and results in shorter training data period requirements and greater robustness and flexibility of the model in responding to change in a building.

Lee and Claridge (2003), building upon the HPCBS work of Haves et al. 2001, describe the foundation of what was to become the ABCAT with the outlined steps for a whole building simulation fault detection procedure, which are applicable to the current ABCAT version. This includes the use of a calibrated simplified first principles model for predicting consumption on a semi-real time basis and an introduction of the benefits of analyzing the cumulative difference of measured and simulation energy consumption. Lee and Claridge performed a retrospective analysis on a building and evaluated several graphical indicators on hourly, daily and monthly levels, and detected three significant schedule changes and two significant component failures with a time series visual analysis.

1.2. Project Goals

The goals of the *Building Commissioning: Innovation to Practice* project are to conduct an integrated research, development, initial deployment, and information dissemination project to quickly overcome owner and industry barriers to the adoption of building commissioning in new and existing commercial and government buildings. Each project element was designed to bring innovative, yet practical, tools and training to commissioning markets across the nation. Together, the suite of tools and activities are meant to help standardize processes for functional testing and building diagnostics – two of the most difficult, time-consuming, and expensive aspects of building commissioning.

Easily accessible functional testing and diagnostic resources will enable commissioning professionals to provide consistently high-quality services quickly at lower cost. As a result, work undertaken through this project was aimed to strengthen the commissioning infrastructure rapidly, overcome owners' price and value barriers, and contribute significantly to the increased adoption of – and benefits from – building commissioning.

1.3. Project Objectives

The objectives of the *Building Commissioning: Innovation to Practice* project were to develop and introduce the market application of innovative yet practical functional performance testing and diagnostic tools and training benefiting commissioning providers and building owners in the states partnering together in this project.

1.4. Report Organization

The remainder of this report discusses the project approach, outcomes, conclusions and recommendations for each of the three major tasks of the project: Functional Testing Guide (FT Guide), Data Analysis Tool, and Automated Building Commissioning Analysis Tool (ABCAT). A chapter has been devoted to each major task organized in the following manner:

Chapter 2: FT Guide

- Element 1: Enhance FT Guide.
- Element 2: Develop Additional Functional Tests for FT Guide.
- Element 3: Develop and Present Commissioning Training Using FT Guide.
- Element 4: Develop and Deploy Functional Testing Checklist Tool.

Chapter 3: Data Analysis Tool

- Element 5: Develop and Deploy Functional Test Data Analysis Tool.

Chapter 4: ABCAT

- Element 6: Develop and Demonstrate ABCAT.

Chapter 2.0 Functional Testing Guide Elements

Project elements 1, 2, 3, and 4 represent work performed by PECI. These project elements aimed to enhance the original *Functional Testing Guide for Air Handling Systems* (FT Guide) and increase use of this resource. A description of the project element approach and outcomes is provided for each element. The conclusions and recommendations section reflects all the work done under project elements 1-4.

2.1. Element 1: Enhance the FT Guide

2.1.1. Project Element Approach

The FT Guide is a resource that helps commissioning providers develop high-quality functional tests more quickly to improve the cost-effectiveness of commissioning. The objective of project element 1 was to produce an enhanced version of the FT Guide with new content and improved functionality and presentation to increase the use of this resource. The following tasks were performed:

- Training conducted through a web conference to a group of commissioning providers from participating states on how to effectively use the FT Guide.
- Provider survey on how the FT Guide was used and tested in practical use.
- Summary of findings that address needed revisions to the FT Guide's content and functionality.
- Revisions made to the FT Guide based on findings and public dissemination of the revised FT Guide.

The first task under element 1 was to determine what was needed to increase the use of this resource. An online training was provided to a group of 14 paid commissioning providers from California, Oregon, Washington, Iowa, and New York who were asked to integrate the guide into their current practices and provide feedback. The input facilitated from these participants covered the way in which the guide was used, what the users thought about the accessibility of functional tests and general navigation, and the rigor of the technical content. Overall, the pilot participants expressed that the FT Guide contains a lot of valuable content that is not available anywhere else, but it can be difficult to use for reference. The information was found to be effective by participants who represented both new and experienced commissioning providers, although they reported using it in different ways. Examples of the various uses of the guide include troubleshooting in the field, modifying or developing functional tests, and as a training resource. Experienced commissioning providers repeatedly demonstrated the need to skip over the background/basic information in the guide, while the less experienced providers expressed the value of these sections. These responses highlighted the opportunity to continue development of the FT Guide on a path where it will remain a resource for different uses and levels of experience and, in some way, also facilitate such a varied application. The responses also demonstrated the need for this type of resource even for the most experienced providers.

In the pilot study, navigation and format stood out as the critical issues for users to find the FT Guide valuable and functional. Responses were split regarding whether an HTML or Word format would be most useful; however, this division seemed to be tied to the participants' desire to download and modify tests for their own use. Aside from addressing the varied audience for the guide, there were critical problems with the format of the resource that often prevented its wholesale use. The original FT Guide was composed of a large number of Microsoft Word documents containing embedded Word hyperlinks that utilized macros. In addition, it was necessary to download all the guide documents into a common directory prior to use. The project dealt with several pilot users who needed technical assistance in downloading the guide and getting it to function with their personal computer systems. Because of the extent and magnitude of these technical problems, it became obvious that these same technical issues would occur for other potential users – likely preventing their ability to access the guide. The expanded content, under development, received favorable reactions in the pilot, and additional planned program tasks (elements 2 and 4) were to focus on developing specific aspects of the guide (functional testing guidance and checklists) that were requested by providers. Therefore, element 1 honed in on a permanent fix for the navigation difficulties encountered by users.

Since the needed improvements were clearly focused on the format, navigation, clarity, and technical performance of the resource rather than on changes to content, the resulting activity was to create an easily accessible online resource with clear navigation. The conversion to an online format was successful, but technically demanding. By converting the FT Guide into an online HTML format, the issue of accessing information by users with different needs was addressed. The existing Word documents as well as the new modules were converted into HTML and placed online. Test documents remained in Word for easy downloading and modification. This effort involved extensive work to fix linkages within the guide and to related resources (Control Systems Design Guide and CTPL), improve presentation and formatting, and create a new navigation system.

Work continued throughout two other related project elements (elements 2 and 4) to effectively integrate all of the FT Guide tools into a seamless online resource. The revised version of the FT Guide was made publicly available at www.ftguide.org.

2.1.2. Project Element Outcomes

The objective of this project element was achieved through careful assessment of pilot feedback and attention to implementing only the most effective structural and functional changes to the FT Guide.

Element 1 project outcomes include:

- Enhancements to the FT Guide that that involved a conversion to a web-based format of the original guide and content recently developed under a separate U.S. DOE-funded project. This effort included a variety of navigation and design enhancements to facilitate use of the guide by commissioning providers with different levels of experience. Peer review feedback confirmed greater ease of use and quick access to specific information. Figure 2 is a screenshot of the new web-based FT Guide interface.

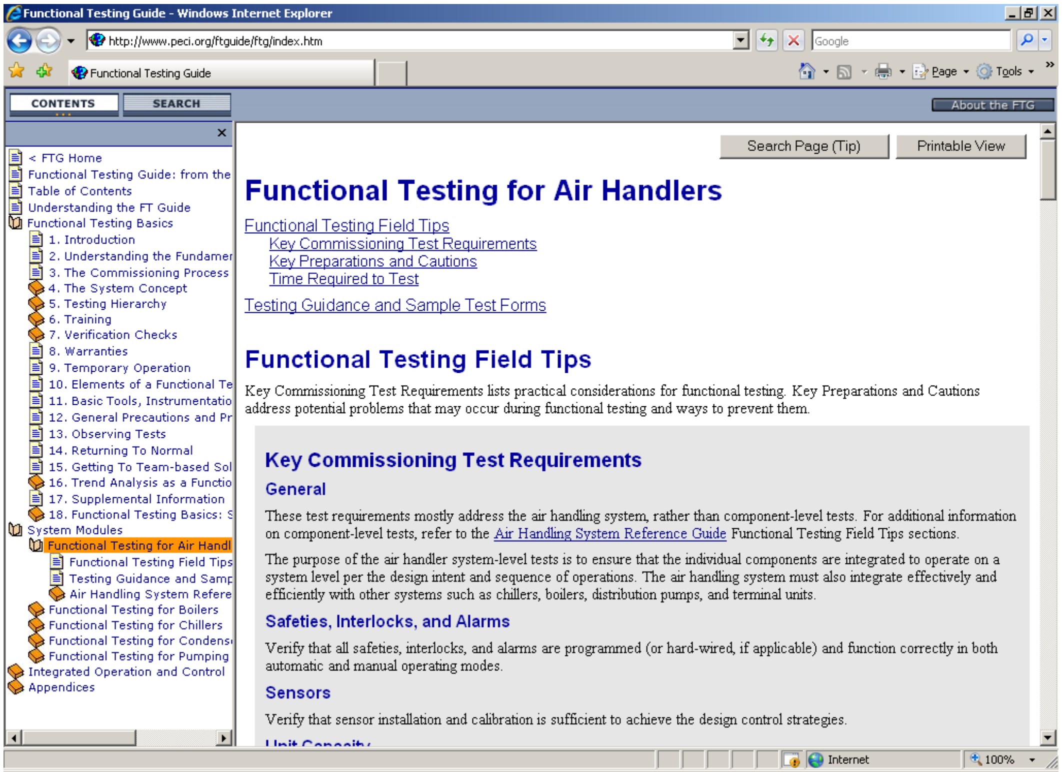


Figure 2. The FT Guide's Online Interface

- An official launch of the publicly available online version of the FT Guide at www.ftguide.org and creation of a direct link to this website from the California Commissioning Collaborative website.

- The conversion of the Control Systems Design Guide into a web-based format that is linked to the main web page of FT Guide. This conversion allows the user to access control system detail using links provided within the FT Guide as well as the Functional Testing Checklist Tool developed under project element 4.

- Presentation of the FT Guide in two sessions at the 2005 National Conference on Building Commissioning, at the 2004 ACEEE Summer Study, and at the Building Commissioning Association Northeast Chapter's Retrocommissioning Summit in February 2006. It has also been presented at "How to Use the FT Guide," a full-day course at PG&E Pacific Energy Center.

2.2. Element 2: Develop Additional Functional Tests for FT Guide

2.2.1. Project Element Approach

The objective of this project element was to enhance the FT Guide with additional content to help commissioning providers develop high-quality functional tests more quickly. The following tasks were performed:

- Development of a list of important functional tests that were not covered in the existing publicly available library of tests or were not covered in adequate detail for a provider to understand how to perform the test. Criteria for test selection were energy efficiency, reliability, and comfort.
- Management of a pilot test and evaluation of general input from the pilot on the value of adding functional tests.
- Development of needed testing guidance documents based on pilot feedback and incorporation of those new resources into the FT Guide.

During the initial FT Guide pilot, commissioning providers mentioned the need for "standards of quality" and "industry-expected standards" in regards to functional testing. Participants were asked to prioritize a list of functional tests that could be added to the guide and fill gaps found in the CTPL. The CTPL has only four main sources of publicly available functional tests. The test list shared in the pilot was expanded to cover functional tests for all of the system modules now included in the FT Guide.

When PECI evaluated general input from the pilot on the value of adding functional tests, they found that the majority of providers write their own tests and prefer their own formats. When using a resource such as the FT Guide, commissioning providers told us that they are looking for guidance on what makes an effective functional test rather than providing test forms that may not fit their existing formats. Using this pilot feedback, PECI moved forward to write testing guidance documents for 14 of the prioritized tests selected using the following criteria: energy efficiency, reliability, and comfort.

The testing guidance documents that were developed under project element 2 describe the steps and potential issues that may arise during functional testing. Commissioning providers may use the testing guidance to expand and improve upon their existing test forms. Example tests based on the testing guidance documents were provided where available. The new testing guidance documents were piloted with a group of commissioning providers by asking them use the testing guidance documents to write functional tests and run them in building projects. Pilot participants provided constructive feedback on the thoroughness of the documents and on how well they streamlined the writing process. This feedback was analyzed and used for revisions.

2.2.2. Project Element Outcomes

The objective of this project element was achieved through careful assessment of the most useful tests for development and through pilot testing of those tests to ensure effectiveness.

Element 2 project outcomes include:

- The development of functional testing guidance documents for 14 prioritized functional tests. The 14 functional testing guidance documents that were developed are listed below:
    - Pump Performance and Impeller Trim Analysis

- Fire and Smoke Control Systems
    - Small Packaged Rooftop Units
    - Large Packaged Rooftop Units
    - Freezestat
    - System Recovery from Power Failure
    - Underfloor Air Distribution Plenum Pressurization
    - Air Handling Unit Reset Strategies
    - Valve Leak-By
    - Envelope Leakage
    - Demand-Controlled Ventilation
    - Radiant Floor Heating
    - Terminal Units-Variable Volume System Flow
    - Writing a Functional Test (general guidance)
- The new functional testing guidance documents were piloted by a group of commissioning providers, who used the guidance documents to write functional tests and run them in building projects. The general consensus from the pilot participants was that using the testing guidance was useful in improving their tests or building new ones.
- The new testing guidance documents were incorporated into the test document tables for each module in the FT Guide and into the FT Checklist Tool developed in element 4.

2.3. Element 3: Develop and Present Commissioning Training Using FT Guide

2.3.1. Project Element Approach

Helping train and expand the infrastructure of commissioning providers while improving the delivery efficiency of experienced providers will improve the cost-effectiveness of commissioning, leading to greater market penetration to achieve energy savings. The objective of this project element was to develop and present training courses for commissioning providers that focused on developing and implementing functional tests using the FT Guide and identifying typical energy saving opportunities commonly found through the retrocommissioning process. The following tasks were performed:

- Development of a one-day interactive training curriculum that teaches test providers how the FT Guide can be used to streamline their functional testing process.

- Development of a four-day curriculum that covers the retrocommissioning process and technical methods for identifying opportunities.
- Creation of instructions on the FT Guide's usefulness in streamlining testing, including standardized spreadsheets on energy and economic analysis.
- Presentation of both the new and existing building commissioning training workshops in New York, California, Iowa, Oregon, Washington, Idaho, and Montana.

One-day interactive FT Guide training:

PECI developed and delivered a one-day interactive training for new buildings to teach commissioning service providers how the FT Guide can be useful in streamlining their functional testing process. The workshop led the audience through the FT Guide's features and worked with participants to develop a functional test for a particular part of the HVAC system at the workshop facility. To complete the learning experience, participants performed a supervised functional test without disrupting other building activities. The curriculum was modified based on the HVAC systems available at each workshop site. PECI engineers presented the new building commissioning training workshops in California, Iowa, Oregon, Washington, and Idaho. Course evaluation forms were completed by all training attendees.

Four-day advanced retrocommissioning workshop:

PECI also developed a four-day advanced hands-on retrocommissioning workshop. The curriculum included standardized spreadsheets for energy and economic analysis. Two experienced commissioning providers reviewed the draft curriculum and their feedback was incorporated. PECI engineers identified training sites and performed a scoping study at each site to identify preliminary findings and gather data. The scoping studies allowed the retrocommissioning training courses to be structured efficiently, focusing the class on problem areas and providing trend data gathered prior to the training workshop.

PECI engineers delivered two existing building commissioning training workshops in New York – in New York City and in Albany. Both training courses were limited to 15 attendees to create an effective learning environment, especially during hands-on activities. These training courses were tailored to the specific facilities in which they took place and required building staff time and access to equipment for the instructor and workshop attendees.

The training provided a brief overview of the retrocommissioning process for existing buildings and presented technical methods for identifying retrocommissioning opportunities (including historical operating information, drawings and specifications, visible indicators, utility consumption, data logging and trending, system flow diagrams, and targeted testing). The training also included instruction on selling retrocommissioning, scoping techniques, HVAC fundamentals, and using the FT Guide to streamline testing. Hands-on activities covered such tasks as a building walk-through and performing a functional test.

Participants at the New York Mercantile Exchange (NYMEX) facility in Manhattan and at the Dormitory Authority for the State of New York (DASNY) building in Albany were given exit surveys to provide the project team with input. Additionally, two attendees in Albany were paid by the project to provide in-depth review of the course material and participate in a telephone interview about the workshop.

One additional advanced retrocommissioning workshop was added to this project element for California with the California Department of General Services (DGS). This training leveraged the curriculum and lessons learned in New York. The training was held at the Attorney General Building in Sacramento, California.

2.3.2. Project Element Outcomes

The objective of this project element was met through the delivery of technical training to 127 engineers and building operators.

Element 3 project outcomes include:

- The completion of two hands-on commissioning training courses in New York. Attendee goals were easily met and the workshops successfully combined classroom instruction with hands-on activities at the training sites. Both New York training sessions took place in buildings whose owners were contemplating full retrocommissioning activities. Post-training, where their building staff was able to participate, the two buildings went on to implement a variety of retrocommissioning measures.
- Collection of participant feedback on the four-day training through exit surveys and two in-depth interviews. In all cases, there was positive feedback on the course (material, presentation, activities). Feedback from workshop attendees who spent four full days immersed in the training and from owners who opened their facilities to the training courses point to a continued support in the market for training. Owners supported the training by providing their facilities free of charge, assigning building staff to participate in a two-day pre-workshop scoping of the building with the instructor, and sending staff to attend the training. The owners came away with a new appreciation for the potential for retrocommissioning and proceeded to work with NYSERDA to continue these efforts.
- Collection of participant feedback on the one-day training courses. On average, attendees gave the training courses a positive rating of 4 (out of 5) and praised the instructor’s teaching style and value of course content.
- The strong positive feedback and high attendance of each training performed under element 3 demonstrated compelling support for a need for more training courses on new and existing building commissioning in the marketplace.

2.4. Element 4: Develop and Deploy Functional Testing Checklist Tool

2.4.1. Project Element Approach

The objective of this project element was to develop a Functional Testing Checklist Tool that can be used by commissioning providers as resource to check their own functional test libraries for completeness or to develop new high-quality functional tests more quickly – improving the cost-effectiveness of commissioning. The following tasks were performed:

- Development of a series of online checklists that link to testing guidance documents, explanations of field tips, and other additional information available through the FT Guide.
- Management of a web conference training session as a kick-off to the pilot of the Checklist Tool. Pilot participants were selected from states participating in the project.
- Modification of the Checklist Tool in response to peer review feedback.
- Incorporation of the revised Checklist Tool into the new online FT Guide resource.

The final piece of the FT Guide development was the development of a Functional Testing Checklist Tool. The original scope of work for element 4 called for an automated tool to identify tests for a particular project. The tool would allow the user to enter general project information such as system type, building activity, and level of testing budget and then generate a checklist of functional tests that should be completed for those particular systems in the operating environment indicated. The checklist was to contain links to the FT Guide for example tests and explanations of benefits and field tips for performing the tests.

Work done through element 1 involving the conversion of the FT Guide to an online document with restructured content, a revamped navigation system, and reconfigured test tables made part of the original objectives for this element unnecessary. What remained was the need for checklists that provided a quick method for verifying that a functional test contained the critical components. As a result, the objectives of element 4 shifted to develop functional testing checklists for the systems covered in the FT Guide. These checklists can be used to check that critical elements are included in functional tests that commissioning providers are currently using and writing. When used online, the checklists link, as originally planned, into the FT Guide to provide background information on particular testing elements.

The FT Checklist Tool was developed as an online resource accessible from the main web page of the FT Guide. The checklists cover 17 different system/component functional tests, i.e. air handling unit (economizer and mixed air, preheat, cooling, reheat, warm-up, fans and drives, distribution, terminal equipment, return relief exhaust), chillers, condensers, boilers, cooling towers, variable air volume and constant volume pumping, and integrated operation and control. Each item on a checklist has a link into the FT Guide – directing the user to background information on why specific elements of a test are important and providing additional information needed for testing. In this way, the checklists are both a quick way to evaluate a test as well as a portal into the FT Guide for specific testing information. The checklists were complemented by the development of a functional test directory (Test Directory) to provide direct access to all the publicly available tests contained in the FT Guide, categorized by system and type of test. As with the other project elements, the Checklist Tool and Test Directory were piloted with a group of paid commissioning providers and feedback was used to make revisions and enhancements.

2.4.2. Project Element Outcomes

The objective of the Functional Testing Checklist Tool was met through the creation of 17 interactive checklists which were incorporated into the online FT Guide. The objective was exceeded through the additional development of a Test Directory – providing direct access to all functional tests in the FT Guide in a single location.

Element 4 project outcomes include:

- Development of a Functional Testing Checklist Tool in HTML format that contains checklists covering 17 different system/component functional tests, i.e. air handling unit (economizer and mixed air, preheat, cooling, reheat, warm-up, fans and drives, distribution, terminal equipment, return relief exhaust), chillers, condensers, boilers, cooling towers, variable air volume and constant volume pumping, and integrated operation and control. Each checklist lists key commissioning test requirements and key preparations and cautions for the systems and components covered in the FT Guide. Checklist items link to testing guidance documents, explanations of field tips, and additional information available through the FT Guide and a Control Systems Design Guide. Figure 3 is a screenshot of the Checklist Tool for air handlers (located at www. peci.org/ftguide/ftct/ftct.htm.)

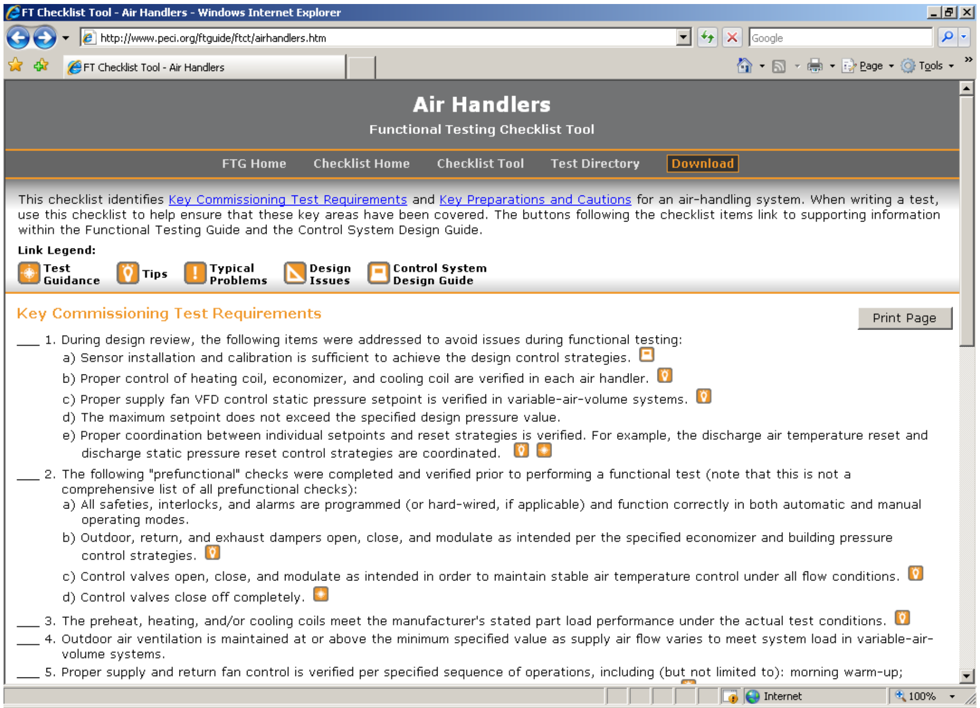


Figure 3. The Online Checklist Tool for Air Handlers

- Development of a Test Directory resource in HTML that provides direct access to all the publicly available example tests and testing guidance documents contained in the FT Guide. Figure 4 is a screenshot of the Test Directory web-page (located at www.peci.org/ftguide/ftct/testdir.htm).

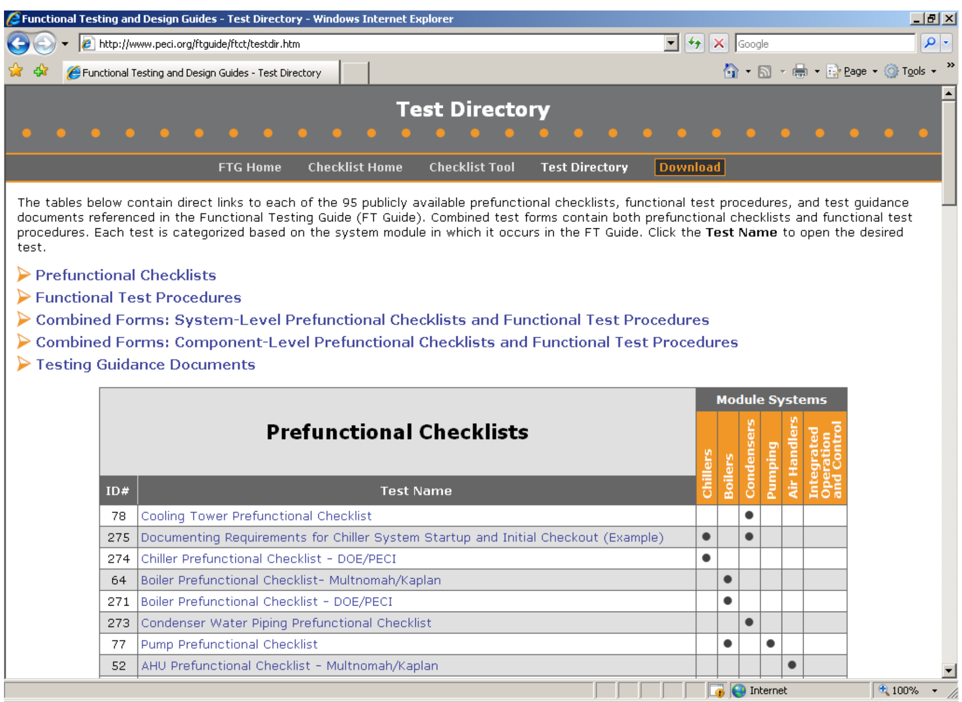


Figure 4. The FT Guide's Online Test Directory

- The pilot testing of the Checklist Tool and Test Directory by commissioning providers from the states participating in the project. Peer review feedback was used it to refine the Checklist Tool.
- The online publication of the Checklist Tool and Test Directory, made accessible from the main web page of the FT Guide at www.ftguide.org.

2.5. Conclusions and Recommendations

2.5.1. Conclusions

The *Building Commissioning: Innovation to Practice* project set out to streamline commissioning practices. The FT Guide is a resource that helps commissioning providers develop high-quality functional tests more quickly – improving the cost-effectiveness of commissioning while making the process more desirable in the market. Work under project elements 1, 2, and 4 produced an enhanced version of the FT Guide with new content and improved functionality and presentation to increase the use of this resource. Training courses performed under project element 3 helped educate and expand the infrastructure of commissioning providers to improve the quality and efficiency of commissioning services and increase cost-effectiveness of commissioning.

2.5.2. Recommendations

Based on feedback from peer reviewers and PECI's communication with commissioning providers, the following projects are recommended for future research to further support the commissioning industry:

- **Add Modules to FT Guide:** A few common systems are not covered in the FT Guide, most notably steam systems and electrical systems. Pilot test feedback pointed to these system types as key areas for improved education in the commissioning industry. Technical content could be developed for these systems that address key commissioning tasks and common problems. Development of these modules could be completed within the current structure of the FT Guide. An estimated funding level of $30,000 per module might be required over a period of five months per module to complete this project.
- **Develop Reference Guide Material for Modules:** The level of detail for each newly developed module (boiler systems, chiller systems, condenser systems, pumping systems), should be further developed to a level of detail similar to the Air Handling System Reference Guide. Pilot test feedback showed interest in more depth on the components that make up the systems. Development of the reference material could be completed within the current structure of the FT Guide. An estimated funding level of $50,000 per module might be required over a period of eight months per module to complete this project.

- **Develop Additional Tests:** Develop additional testing guidance documents for key areas and add them to the FT Guide Test Directory. A sample of the recommendations from the FT Guide pilot reviewers is listed below.
    - Electrical tests: UPS systems, breakers, emergency generators, ATS, fire alarm, grounding, panel board
    - Ground-source and water-source heat pump systems
    - Valve/damper control loop tuning
    - Lighting controls
    - Fire alarm systems
    - Cooling tower free cooling and winter operation
    - Lab fume hood systems and exhaust

  An estimated funding level of $20,000 per test including pilot testing and refinements might be required over a period of two to three months per test to complete this project.

- **Provide specialized commissioning training opportunities**: Additional training is needed to continue to expand and improve the skills of the commissioning provider pool as industry growth outpaces supply of qualified providers. To support this growth in training needs, it is necessary to also provide specialized training for instructors to help expand the instructor pool ("train the trainer"). Training building operators on commissioning is also key. Training areas could include:
    - Introductory orientations for new practitioners and hands-on technical training for experienced practitioners.
    - Training that integrates with the requirements and standards of LEED, Title 24 and other future codes and standards will allow commissioning providers to offer added value and enhanced services to their clients.
    - Building operator training to address how facility staff can be involved in commissioning and retrocommissioning projects and their key role in tracking building performance over time to improve persistence.
    - Commissioning curriculum development for colleges and universities, including specialized training for instructors on how to deliver effective curriculums on building commissioning.

  An estimated funding level of approximately $25,000 - $50,000 per newly developed training curriculum and delivery of the training might be required over a period of six months per curriculum to complete this project.

2.5.3. Benefits to California and Other Participating States

Initial deployments of the resources and tools developed through the project benefited California as well as other participating states. The enhanced FT Guide is now a publicly available internet resource that exposes commissioning providers to practical information about system performance and energy efficiency opportunities and helps to streamline functional testing efforts through the use of testing guidance documents, sample functional tests, and the Checklist Tool. A link to the FT Guide online resource has been placed on the California Commissioning Collaborative website.

Many commissioning providers, facility managers, and mechanical engineers benefited from attending the building commissioning training courses offered through the project. Through hands-on activities and instruction, training attendees developed an understanding of the retrocommissioning process, learned technical methods for identifying opportunities, and developed skills in writing and performing functional testing. The training courses also helped to expand the market awareness of the benefits of commissioning in the states in which they were held (New York, California, Oregon, Washington, Iowa, and Idaho).

Chapter 3.0 Element 5: Develop and Deploy Functional Test Data Analysis Tool

3.1. Project Element Approach

The objective of project element 5 was to develop an automated functional data analysis tool that will be used in the field to analyze and display data produced by functional performance tests on air handling units.

The Lawrence Berkeley National Laboratory (LBNL) developed and field tested a Functional Test Data Analysis Tool (FT Data Analysis Tool) through this project. This tool uses a library of data analysis routines to analyze test data obtained by a commissioning provider and entered manually into the tool, which runs on a lap-top computer. Component-level FDD, which is the basis of the approach used to develop this tool, uses a bottom-up methodology to detect individual faults by analyzing the performance of each component in the HVAC system (Hyvärinen and Kärki 1997, LBNL 1999, Haves & Khalsa 2000). The tool assesses performance of the mechanical components of an air handling unit – fans, mixing box, heating coil and cooling coil - and identifies the likely causes of failure.

The data analysis is based on methods for automated fault detection and diagnosis developed in previous projects funded by the California Energy Commission and U.S. DOE (Xu *et al.* 2005). Quantitative models of component performance are used to represent correct operation. A significant difference between the measured and predicted output of the component is taken to indicate the presence of a fault. A set of expert rules is used to analyze the variation between the measured and predicted output over the operating range in order to diagnose the nature of the fault. Inferencing is used to relate linguistic rules to continuous variables, avoiding the threshold problems associated with simple rule-based diagnostic systems. The design and the intended use of the tool as of mid-2006 are described in detail in Haves *et al. (*2007).

Diagnostic Method

One approach to automating both commissioning and performance monitoring is to use computer-based methods for fault detection and diagnosis (FDD). The tool uses component-level HVAC equipment models implemented in the SPARK equation-based simulation environment (SPARK 2004). When used for commissioning, each model is configured using design information and component manufacturers' data. Next, the behavior of the equipment measured during functional testing is compared to the predictions of the model; significant differences indicate the presence of one or more faults. The model is used to predict the performance that would be expected in the absence of faults. A comparator is used to determine the significance of any differences between the predicted and measured performance and hence the level of confidence that a fault has been detected.

The development of a test procedure for a particular component, subsystem or system starts with the specification of the faults to be detected. In the work reported here, test procedures were designed with the aim of detecting all the common faults in air handling units. Xu *et al.*

(2005) includes a list of common faults for the mixing box, coil/valve, and supply/return fan subsystems. The major faults of these three subsystems can be classified into the following five groups:

I) Faults detectable at minimum control signal, e.g. leakage

II) Faults detectable at maximum control signal, e.g. coil fouling, undersized equipment

III) Faults detectable because the target component fails to response to change in control signals, e.g. stuck actuator, bad communication between controller and actuator

IV) Faults occurring across the operating range and detectable from the response of the target components in the middle range of the operation, e.g. hysteresis, sensor offset

V) Faults related to control, e.g. poorly tuned controller, incorrectly implemented sequence of operations

The faults are grouped in this way because it is relatively easy to determine which type of fault exists based on a simple analysis of the performance data generated during the tests. Project resources did not permit incorporation of closed loop tests in the first version of the tool; therefore faults such as incorrect control programming or loop tuning are currently not detected. Within each group, a more detailed rule based fault diagnosis method can be then used to further diagnose the exact fault.

The test procedures are designed to detect all the faults by exercising the systems over their full range of operation. Although the functional tests presented here for the mixing box, fan and coils differ in detail, the general ideas are the same. Faults in Group I, II and III can be detected by analyzing the performance at each end of the operating range. If the models used to analyze the results of the test are steady state models, only measurements taken when the system is close to steady state can be used. At each step, a steady state detector verifies that the system is in steady state before the data are recorded and the test moves on to the next step.

Table 1 shows the minimum sequence of operating points for an open-loop mixing box test. The control points required for the test are:

- Return air temperature (T_{ret})
- Outside air temperature (T_{out})
- Mixed air temperature (T_{mix}) (if present and considered reliable)
- Supply air temperature (T_{sup}) (used when mixed air temperature sensor is missing or unreliable, subtract assumed/calculated temperature rise across supply fan to estimate mixed air temperature)
- Damper position (control signal)
- Calculated Point: $OAF = \frac{Tmix - Tret}{Tout - Tret}$

A similar sequence of operating points is used for the open-loop heating and cooling coil tests.

Table 1. Open-Loop Test Sequence for Mixing Boxes

Step number	Demanded damper position (%)	Fault to be detected
1	0	Outside air damper leakage
2	10	Damper/actuator mismatch
3	50	Non-linearity
4	90	Damper /actuator mismatch
5	100	Recirculation air damper leakage
6	50	Hysteresis

Use Case

In new construction, the FT Data Analysis Tool is designed to be used after the start-up tests and the testing and balancing (TAB) have been performed. In its present form, the tool tests the mechanical equipment, including the sensors and actuators, but does not test the control programming or loop tuning. Closed loop testing of controlled performance could be added in a subsequent development phase. The design of the tool is based on the following assumptions:

- The sensors and actuators have been connected to the field panels, though the network connecting the field panels to the operator workstation may not be installed or working. The available measurements may be from a combination of energy management and control systems (EMCS) sensors and temporary instrumentation.
- Testing and Balancing (TAB) and pre-functional checks (wiring checks, stroking of actuators, etc.) have been performed but not necessarily completely or correctly.
- The information available to the commissioning provider includes the mechanical drawings including the coil schedules and the fan information in the air handling unit schedule and catalog data for the fans.
- The commissioning provider may wish to enter information on all the air handling units to be tested into the tool off-site, prior to the testing.

The tool is semi-automated in that the test data are entered manually and the analysis of these data is performed automatically. This has the advantages of avoiding the communication problems associated with extracting data automatically from control systems, particularly legacy systems, and allowing the test data to come partly from temporary instrumentation. Automated analysis provides a degree of repeatability and objectivity to the analysis of the data that may be helpful when communicating the existence of problems and assigning responsibility for fixing them. When using the semi-automated tool described here, it is the responsibility of the person conducting the test to identify when the system has attained an adequate approximation to steady state after each step.

The modules developed to-date test the operation of the mechanical equipment in built-up systems, including the sensors and actuators, by comparing the expected and observed steady state behavior of the supply fan, the return fan, the mixing box and the heating and cooling coils. The tests can be performed in open loop by overriding the control signal to the actuator or in closed loop by changing the appropriate setpoint. Open loop tests do not test the operation of the controller; however, they have the compensating advantage that they do not rely on the controller being correctly configured and tuned in order to test the mechanical equipment.

User Interface

A substantial part of the work reported here involved the development of a convenient user interface to facilitate manual entry of test measurements. The tool was designed to be useful to commissioning providers conducting functional tests in both new and existing building environments, as well as to building owners and operators that conduct routine tests periodically to check their HVAC system performance. A preliminary graphical display showing the measured performance versus the expected performance and highlighting significant differences that led to the unit failure was produced for one component (the mixing box). The design of the tool was reviewed periodically by a Technical Advisory Group (TAG). The TAG was generally supportive of the overall approach to the design of the tool and provided feedback on design details.

The tool is designed to be run on a laptop computer. The tool can be configured with the necessary design information and catalog data either on-site before or in the course of the testing or off-site, e.g. in the commissioning provider’s office prior to going on site.

Configuring the Tool – Site and Air Handling Units

The first step in configuring the tool is to specify the characteristics of the site, which could be a single building or a group of buildings, such as a campus. The next step is to specify the name and characteristics of each of the air handling units to be tested. If there are multiple buildings on the site, the name should include the name of the building. The characteristics, which are mainly used to estimate the effect of fan temperature rise on the functional tests of the thermal components, are shown in Figure 5.

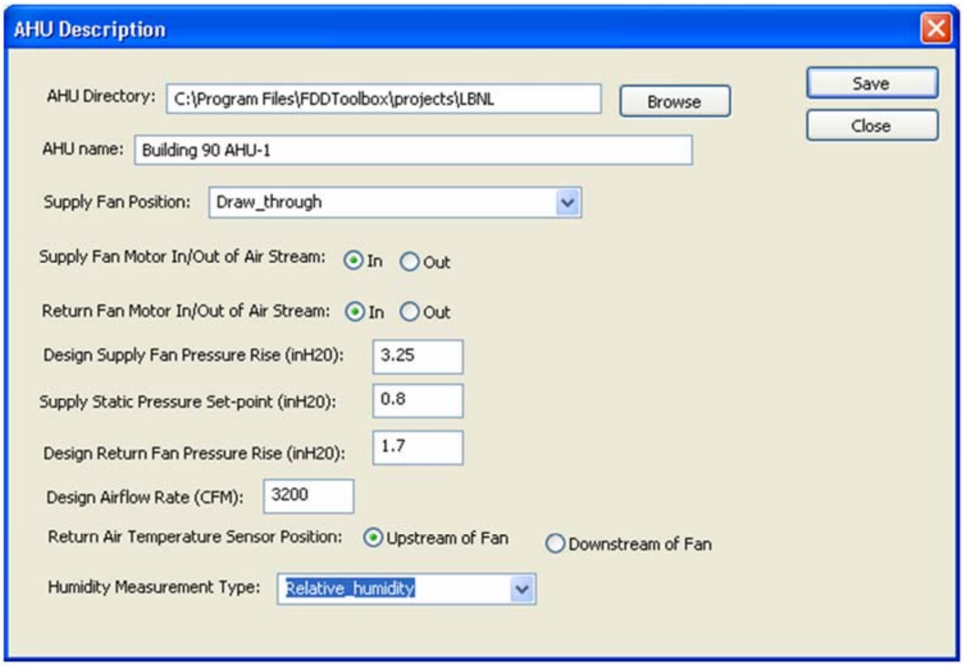


Figure 5. Air Handling Unit Description Window

The position of the supply fan before or after the coils determines whether the supply fan temperature rise should be added when inferring the coil inlet air temperature from the outside or return air temperature or subtracted when inferring the coil outlet air temperature from the supply air temperature. (It is assumed that the mixed air temperature sensor, if it exists, is unreliable.) The position of the fan motor determines whether the inefficiencies of the motor and the belt contribute to the fan temperature rise.

Configuring the Tool – Components

Fan. Figure 6 shows the configuration screen for a fan subsystem. Two catalog data points are required for the fan itself, together with efficiency values (assumed constant) for the motor, belt and VFD. The design rotation speed, turndown and control signal information are required to check the setup and linearity of the VFD. If information for only one operating point is available, the second point may be omitted; the tool then uses a default value for the scope of the pressure flow rate relationship and assumes the efficiency is constant.

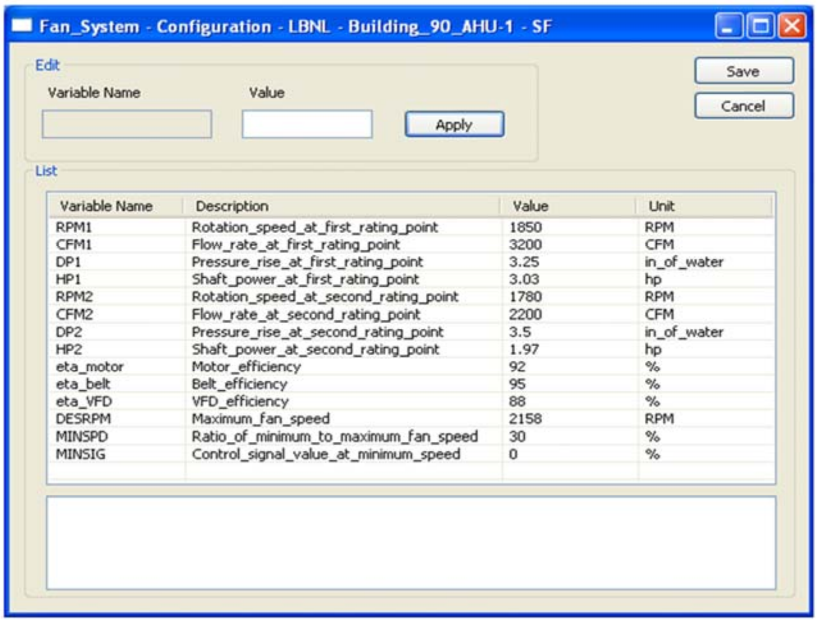
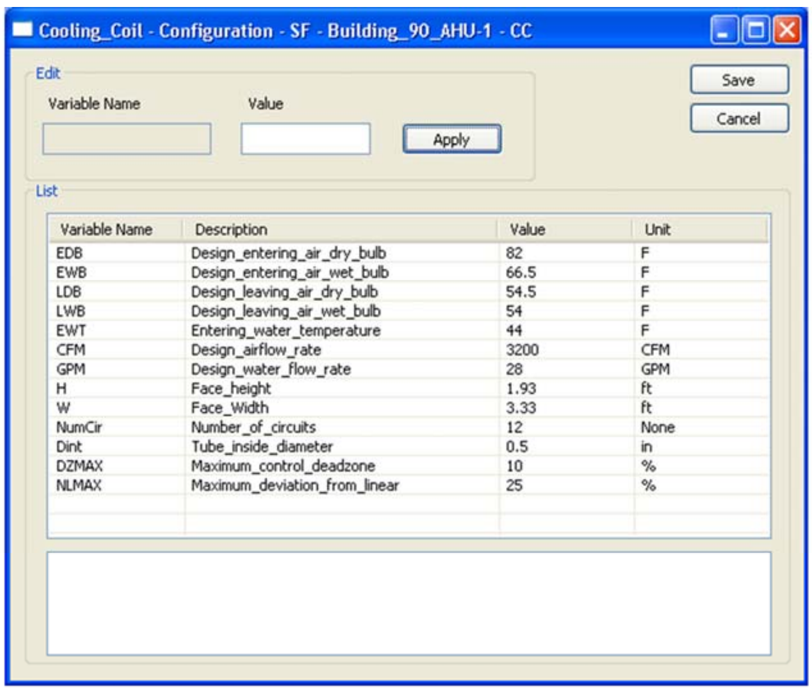


Figure 6. Fan Description Window

Cooling and Heating Coils. Figure 7 shows the configuration screen for the cooling coil. The rating point information from the coil schedule is supplemented by information required to calculate the air and water velocities from the corresponding volumetric flow rates. The face area is required to calculate the air velocity and the number of circuits and the tube diameter are required to calculate the water velocity. The number of circuits may be difficult or time consuming to determine in some situations; in such cases, the tool can use a default value of 6 $ft.s^{-1}$ for the water velocity under design conditions. The maximum acceptable deadzone between the control signal coming out of a limit and the valve starting to move so as to affect the water flow is used in the test for incorrect adjustment or range mismatch of the control valve and the actuator. The maximum acceptable deviation from linearity at the midpoint of the active range is used to check for poor authority or incorrect control valve characteristic.



Variable Name	Description	Value	Unit
EDB	Design_entering_air_dry_bulb	82	F
EWB	Design_entering_air_wet_bulb	66.5	F
LDB	Design_leaving_air_dry_bulb	54.5	F
LWB	Design_leaving_air_wet_bulb	54	F
EWT	Entering_water_temperature	44	F
CFM	Design_airflow_rate	3200	CFM
GPM	Design_water_flow_rate	28	GPM
H	Face_height	1.93	ft
W	Face_Width	3.33	ft
NumCir	Number_of_circuits	12	None
Dint	Tube_inside_diameter	0.5	in
DZMAX	Maximum_control_deadzone	10	%
NLMAX	Maximum_deviation_from_linear	25	%

Figure 7. Cooling Coil Description Window

The input configuration process for heating coils is similar to that for cooling coils, expect in two respects:

- The humidity information is omitted.
- The number of rows is included for use in determining the appropriate effectiveness-NTU relationship to use in the model.

Mixing Box. The mixing box model is purely prescriptive; no attempt is made to simulate the expected performance based on the damper characteristics and air handling unit geometry. The only configuration data required by the tool are:

- The maximum acceptable deadzone between the control signal coming out of a limit and the dampers starting to move so as to affect the air flow
- The maximum acceptable deviation from linearity at the mid-point of the active range as discussed above.

As in the case of the coils, these values must be defined using engineering judgement, based on the application. The default value for the maximum acceptable deadzone is 10 percent and the default value for the maximum acceptable deviation from linearity is 25 percent, which corresponds to a variation in gain of 3:1 across the operating range.

Functional Testing

Functional Testing. The tool has been designed to analyze the results of tests of specific mechanical components that consist of a series of steps in operating point. The preferred sequence for testing the different components is to start with the fans. Correct operation of the supply and return fans is necessary for correct pressures in the mixing box. The calculations of the temperature rise across the supply fan and the return fan, which are used to correct the supply and return air temperature measurements in the tests of the mixing box and the coils, also depend on the correct operation of the fans. The mixing box should be tested before the coils, since damper leakage could cause the actual mixed air temperature – and hence coil entering temperature – to differ from the assumed value based on the position of the dampers and the measurement of outside or return air temperature. If both a heating coil and a cooling coil is installed, the order of testing is immaterial, as long as the coil not under test can be turned off effectively, e.g. with isolating valves.

Fan capacity and efficiency. The control signal to the VFD, the rotation speed, the flow rate, the pressure rise and the electric power are entered by the user and the date and time are generated automatically by the tool. In general, not all of these measurements will be available from the EMCS and portable instruments will be required for some measurements. The fan model embedded in the tool predicts the pressure rise and electric power from the rotation speed and the flow rate using the catalog data entered in the configuration phase. These values are then displayed, along with uncertainties estimated using assumptions about the accuracy of the measurements that are hard-coded into the tool. The purpose of the tool is to detect and diagnose substantial faults. The tool compares the measured and expected pressure rise and electric power. If either of the differences exceeds the combined uncertainties, a fault is reported.

VFD. The set-up and linearity of the VFD is tested by commanding three different fan speeds: maximum, mid-range and minimum, and measuring the resulting rotation speeds. The values are entered into the tool, which then checks for a linear relationship between measured rotation speed and control signal. The mid-range signal is approached from above and below and the resulting rotation speeds compared to check for hysteresis.

Mixing box and coils. Figure 8 shows the functional test screen for the mixing box. The screens for the fan and the cooling and heating coils are similar. The top section of the window is where performance and analysis data are entered and displayed. Data can be entered after each step of the functional test sequence or all the data can be entered together at the end of the sequence, whichever is more convenient for the user. If the data are entered after each step, the tool can analyze the data entered up to that point in time and flag a major fault that would render the continuation of the test to be pointless.

The section in the middle of the window is used to show the progress of the tests and to display the final test report. The tool can also generate a report in text format for printing. The test report consists of three parts. The first part contains general information about the test and also the performance data entered by the user. The second part shows the fault analysis at each step. The last part is a summary of the results of the complete test, including a numerical measure of the confidence that the operation is correct or incorrect and that particular faults have been diagnosed. The section at the bottom of the window provides guidance on the test sequences. The users can easily switch between the action, explanation and what to expect sections.

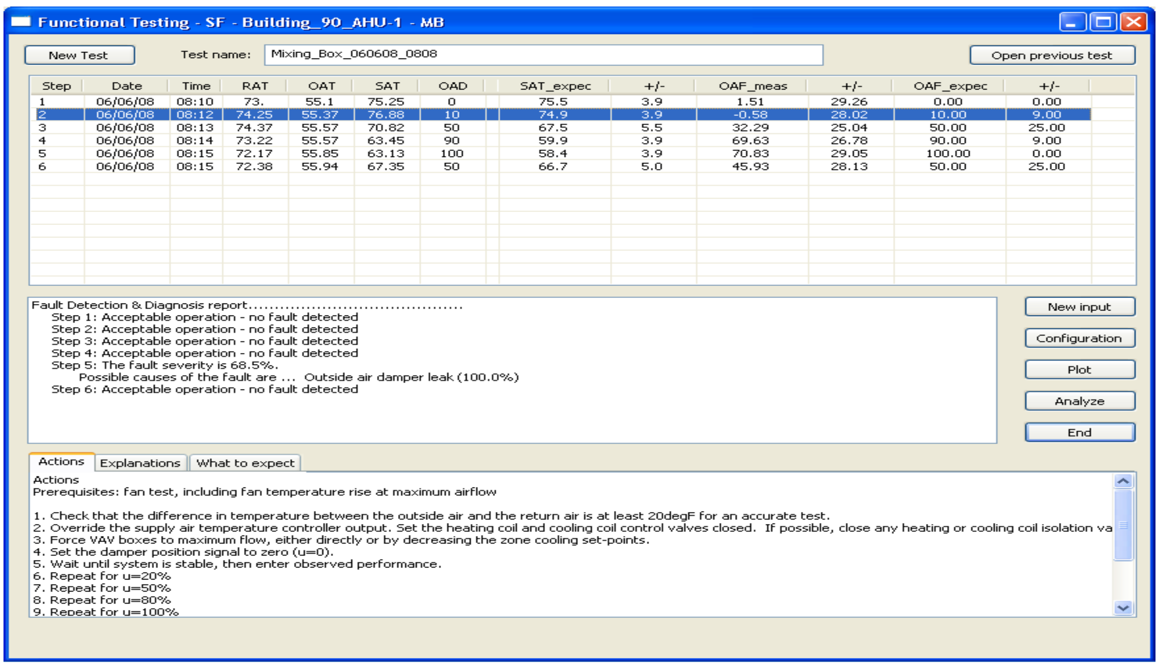


Figure 8. Mixing Box Functional Test Screen

Testing

The first testing of the tool was performed at the Iowa Energy Center's Energy Resource Station, which contains multiple commercial EMCS, as well as three complete air handling systems, and has a staff with experience in the development and testing of fault detection and diagnostic tools. Results from the tests and feedback from the staff were then used to refine the design of the tool. The tool was then field-tested by commissioning providers – two in California and two in New York. The commissioning providers were tasked with providing feedback in four areas:

- The intent and usefulness of the tool
- The design of the tool and its approach to achieving the intent of the tool

- General operation of the tool and ease of use
- Possible extensions of the tool that would enhance the tool's usefulness

The feedback from the commissioning providers that tested the tool primarily addressed the usability of the tool, focusing on the user interface and the data requirement, and also addressed the question of the when, how and by whom the tool could most usefully and effectively be applied.

Several factors limited the ultimate technical scope of the tool. From the time the project was proposed to the time it was started, it was expected that R&D on the underlying diagnostic methods used in the tool would continue to be funded by DOE, which turned out not to be the case. In addition, significant programming problems were encountered during the development of the tool. As a result, the scope was limited to open loop tests of individual components, even though the original intent had been to include the option of closed loop testing, which would simplify the test procedure in some cases, as well as allow the tool to detect certain control problems.

3.2. Project Element Outcomes

The design of the tool was refined between mid-2006 and the end of the project. In the last nine months, modifications of the tool were primarily aimed at reducing the input data requirements. For example, the absolute requirement for fan performance data at two distinct operating points was relaxed. This allows data for the design point, taken from the mechanical drawings, to be used in place of manufacturers' data, with the project making an assumption about the slope of the head curve.

The first stage of testing of the tool was performed at the Iowa Energy Center Energy Resource Station (ERS). The first set of tests was performed using air handling units operating normally. This allowed the models, and the process of using manufacturers' data to configure the models to represent the particular equipment under test, to be tested. The second set of tests was performed with real or simulated faults introduced into the equipment being tested, which tested the ability of the models to discriminate between correct and faulty operation and also tested the fault diagnosis procedures.

The overall outcome of the tests was to confirm the validity of the model-based approach to fault detection and the rule-based approach to fault diagnosis. A number of programming problems and inconsistencies in the rule base were revealed by the testing and subsequently corrected.

Field testing was performed in May 2007 by two commissioning providers in New York (Dome-Tech and Robson Woese) and two in California (TRCsolutions and QuEST). Due to timing and other constraints, QuEST was not able to use the tool to analyze the results of active functional testing. The results of applying the tool to the analysis of trend data for a mixing box confirm that, as expected, the tool, in its current form, is not able to detect control problems. The feedback from the commissioning providers that tested the tool is summarized below:

Intent and usefulness of the tool:

Three of the four evaluators agreed that the tool could be very useful for building maintenance personnel and building owners to verify the correct operation of their equipment rather than hiring an outside commissioning provider. One evaluator suggested that the tool could be used to investigate problems found by performance monitoring or other functional testing, both for new and existing equipment.

On the issue of tool usefulness for commissioning and retrocommissioning providers, the evaluators agreed that the tool could be helpful in improving the speed and efficiency of their testing, but were unsure about the level of this improvement. One issue is the availability of data for tool configuration. The general lack of documentation encountered in older buildings limits the usefulness of the tool for retrocommissioning, hence the recommendation that the best application of the tool might be by maintenance staff, who would need to make a one-time effort to gather the configuration data but would reap the benefit every time the tool was used in a periodic re-testing program.

The design of the tool and its approach to achieving the intent of the tool:

In general, all the evaluators reacted positively to the current design structure, in particular, the approach of giving step-by-step instructions for each test and then telling what to expect and giving possible reasons for abnormal behavior. There were a number of suggestions for improvements. Most of the evaluators addressed the issue of documentation and dynamic help in some way.

General operation of the tool and ease of use:

The evaluators found a number of software problems, most of which were related to the user interface. None is thought to be inherently difficult to remedy.

Possible extensions of the tool that would enhance the tool's usefulness:

The recommendations made by the evaluators can be categorized into four sets:

1) Interface. The majority of the comments were suggestions for improving the interface, including:

   - dynamic (context-sensitive) help and documentation
   - improved graphical display of diagnosis results and the capability to generate a report in the form of a PDF or .txt file
   - easier navigation, e.g. display a list of recently accessed files or directories (depending on context)
   - greater robustness, e.g. tool generates appropriate error messages when functions used out of sequence or input data are incomplete

2) Extension to other components and features. Another set of recommendations concerned extension of the tool to other components and addition of features, including:

- fans with inlet guide vanes
- VFDs for exhaust fans and pumps
- air filters
- indication of the cost of energy waste due to faults detected
- control loop diagnostics (since all data are entered by hand, this would need to be restricted to faults that do not cause hunting)

3) Test procedures

- change the recommended test procedure for supply and return fans to reduce the number of steps
- include alternative measurement methods, e.g. provide for separate current and voltage measurements instead of electric power input for the fan module

4) Documentation

- hardcopy documentation of process, test procedures, instrumentation required
- comprehensive work example – hardcopy and/or on-screen animated tutorial generated by automated screen capture
- documentation of the theory behind the diagnosis mechanism
- better documentation of the format and content of the internal files created by the project

3.3. Conclusions, Recommendations, and Benefits

3.3.1. Conclusions

A prototype tool for the analysis of functional tests on air handling unit components was produced and tested by four commissioning providers. The general response of the testers was favorable; however, it is clear that further work is required to produce a tool that is more robust and easy to use. The testers identified two uses for the tool not anticipated at the beginning of the project: use by facility maintenance personnel and use as the basis of a training tool. Specific conclusions from the field test are provided below:

- The intent and design of the tool are fundamentally sound.
- Further development and testing are required to improve its usability and robustness.
- The tool is most suitable for periodic testing of air handling units by maintenance staff.

- The tool is potentially useful to commissioning providers, particularly for junior engineers.
- The use of the tool in retrocommissioning may be limited by the difficulty of obtaining basic design/as built data.
- Extending the tool to include closed loop testing would make the tool more attractive by reducing or eliminating the need for the assistance of a controls technician.
- The tool has potential as the basis of a training tool for commissioning.

In addition to the further work required to produce a tool that is robust and easy to use, the following are required to produce a commercially viable product:

- An organization that can maintain the tool (e.g. ensure that the tool functions with future versions of Microsoft Windows), distribute the tool, and provide user support. Such an organization should have both computer expertise and knowledge of building commissioning and operations.
- A business case for the maintenance and support of the tool. In the long term, it is possible that revenue from sales and support might generate sufficient income. In the short to medium term, one or more state energy offices or large utilities, or a consortium of such organizations would need to provide financial support. The justification for such support would presumably depend on the use of the tool by state agencies (e.g. university campuses) or in retrocommissioning and/or training programs.

3.3.2. Recommendations

Commissioning providers that evaluated the tool held the opinion that the tool would be beneficial in improving HVAC system performance if it were further developed. In view of the potential of the tool design and the relatively modest additional resources that would appear to be required to significantly improve its robustness and ease of use and to extend its scope to other components and subsystems found in conventional HVAC systems, it is recommended that the following additional R&D work be supported:

- Implement the improvements to the operation of the tool, especially the interface, recommended by the commissioning providers who evaluated the tool.
- Extend the tool to include other components or component variations in order to provide more comprehensive treatment of the range of equipment types and configurations encountered in air handling units.
- Extend the scope of the tool to include closed loop testing in order to test some control functions and reduce the need for controls technician assistance in testing.
- Develop a training tool for functional testing and troubleshooting based on the tool.

Estimated funding level required:

- The improvements and extensions to the tool for use in commissioning described above could be implemented and properly tested for $100,000 - $200,000.
- Development and testing of a training tool based on the tool would cost an additional $100,000 if performed within the framework of an existing training tool such as HVAC ePrimer or approximately $200,000 if developed from scratch.

Estimated time required to carry out the recommended next steps:

- Improvements and extensions for commissioning would take 12-18 months, including comprehensive field testing.
- Development and testing of a training tool would take approximately 2 months if incorporated in HVAC ePrimer, approximately 18 months if stand-alone.

3.3.3. Benefits to California and Other Participating States

Widespread deployment of a tool, such as the FT Data Analysis Tool, will enable the energy performance and controllability of air handling units to be tested more easily. The improved performance made possible by this testing will benefit building owners through lower utility bills, building occupants through improved comfort control and the local and global environments through reduced emission of pollutants. The development to date of the prototype tool is a starting point for a more comprehensive tool that will enable greater performance benefits by facilitating the functional testing of more systems in buildings.

Chapter 4.0 Element 6: Develop and Demonstrate Automated Building Commissioning Analysis Tool (ABCAT)

4.1. Project Element Approach

Past approaches to fault detection and diagnostics (FDD) in HVAC, whether focused at the whole building, system or component level, have not been successful in transitioning to marketable products. The goal of the ABCAT is to become a simplified, robust, marketable, cost effective alternative to the high priced, heavily sensor reliant existing tools that have failed to make significant market penetration. The ABCAT uses a simplified first principles model to predict heating and cooling energy at the whole building level which deviates from the data driven or black box models that have been used in other systems (Haberl and Claridge 1987; Haberl et al. 1988; Dodier and Kreider 1999). The advantages gained in this approach are increased accuracy and greater robustness to changes in the building with less training data required. In addition, by involving the user, keeping the tool simplified, and focusing on faults that truly have a significant cost impact at the whole building level, this work takes into account the lessons learned from the real building trials of other tools.

The objectives of this project element were to develop the Automated Building Commissioning Analysis Tool (ABCAT), from work originally initiated by Lee and Claridge (2003) and Lee et al. (2007), to an advanced prototype stage and demonstrate its effectiveness in live building implementations.

Summarized below are the specific developmental goals for the ABCAT in this project:

- Establish engineering and software requirements.
- Commission each of the buildings selected as test beds to establish the base case.
- Develop an interface protocol, within the budget, between ABCAT and at least one major control system to allow for some form of automated data exchange.
- Establish and/or select metrics to express significant changes in building performance that normally are not detected or flagged which will lead to suboptimal performance.
- Add reporting routines with a user interface for manual data entry.
- Modify the tool, using field data from three test bed sites in Texas and Nebraska and feedback from the testers in New York.

The implementation of the ABCAT in buildings of various size, shape, space utilization and HVAC system types tests the current capabilities of the ABCAT. The lessons learned from these implementations will help to shape the ABCAT in future developmental stages and bring it a step closer to end users in the marketplace. The following are the set testing objectives of the project:

- Test the following building types:
    - One building served by the Texas A&M Central Plant
    - One high performance building in Texas
    - One high-rise commercial building in Nebraska
    - Two - four buildings in New York
- Provide training and support to New York testers
- Provide summary of feedback on ABCAT testing and modifications based on feedback

The FDD approach to be undertaken in this research will be applied to the whole building energy consumption level and is simplified to aid in the practicality of its implementation outside of the university and research lab setting. A SEAP (Knebel 1983) simulation model was developed specifically for the ABCAT and is used to predict the cooling and heating energy consumption for the buildings in the study. The types of systems available for modeling include: Single Duct-Variable Air Volume or Constant Volume (SDVAV or SDCV) with terminal reheat, Single Zone Heating and Cooling (SZHC), Dual Duct Variable Air Volume or Constant Volume (DDVAV or DDCV) and Dual Fan Duct Dual Variable Air Volume (DFDDVAV). The level of diagnostics to be provided in the ABCAT approach will focus on providing key characteristics of the problem, which can limit the possible causes to several options rather than pinpointing the cause.

Initial Setup and Execution

The ABCAT is initially set up in a building through the following sequence of steps:

1. **Define a Baseline Consumption Period and Collect Baseline Measurements.**

   The baseline period should correspond to a time when the building mechanical systems are known to be operating correctly, typically post new building commissioning (Cx) or retrocommissioning (RCx). The length of baseline can be a minimum of four weeks if during the swing seasons where a wide range of outside air temperatures is experienced and heating and cooling systems are both operating. Recent work by Liu et al. (2008) indicates that in some cases, two weeks of data should be adequate. Required measurements include whole building heating (WB_{Heat}) whole building cooling (WB_{Cool}), whole building electric (WB_{Elec}), ambient outside air temperature and relative humidity or dew point temperature, all recorded in hourly intervals. Figure 9 describes the consumption monitoring that is required for the ABCAT. Ideally the WB_{Heat} and the WB_{Cool} would be obtained by Btu metering of chilled and hot water, but these values could also be obtained by modeling the chiller and boiler if interval meters exist that monitor chiller electric loads and natural gas consumption.

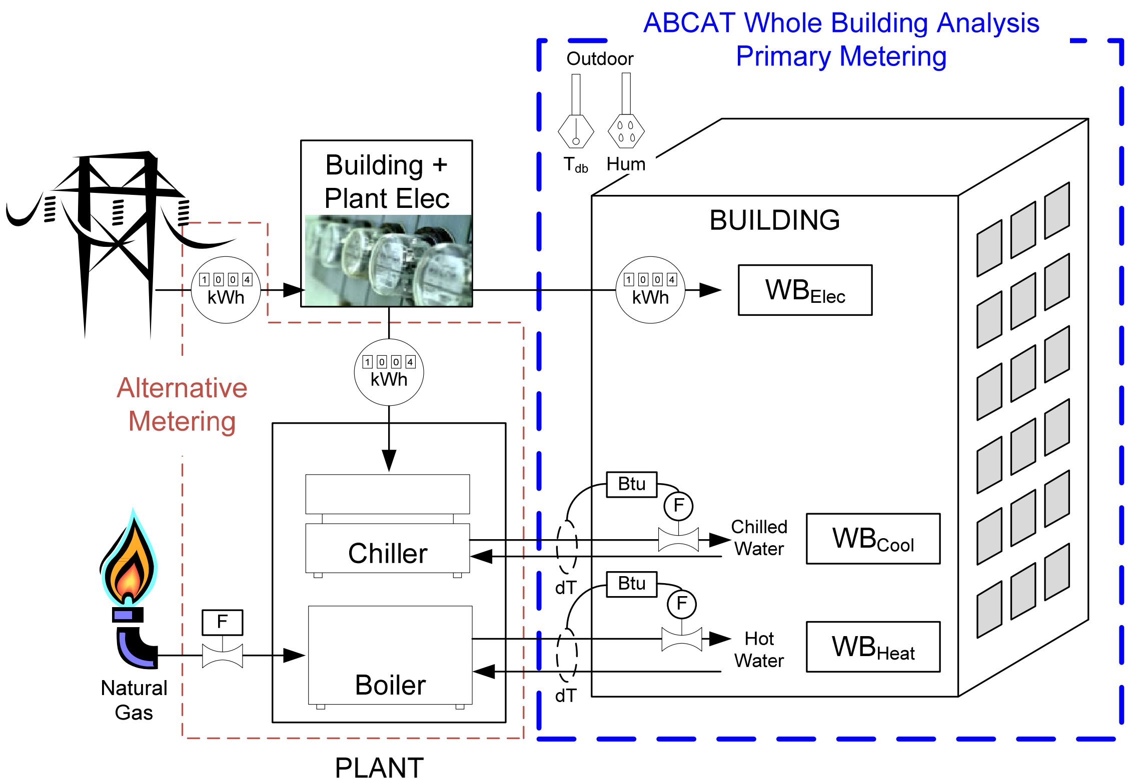


Figure 9. Consumption Metering Requirements for the ABCAT

Source: Portland Energy Conservation, Inc.

2. **Obtain Building and Air Handling Unit System Details.**

   The key characteristics of the building and its HVAC systems that must be included in the model are the: (1) Envelope Area and Heat Transfer Coefficient, (2) Solar Radiation Load, (3) Internal Heat Gain from Equipment and Lighting (taken as fraction of measured electric load), (4) Deck Temperature Schedules, (5) Maximum and Minimum Air Flow Rates, (6) Outside Air Intake and Economizer Settings, (7) Occupancy Schedule, (8) Air Handling Unit Operation Schedule and (9) Humidification Operations. Liu et al. (1998) describes the steps for an initial value selection of these parameters in a model with similar input requirements as the ABCAT.

3. **Establish Initial Values of Inputs for the Simulation Model and Calibrate the Model.**

   Generate an input file for simulation based on measured data and system information and calibrate or tune the model inputs until desired accuracy is achieved.

4. **Correct for Bias in Model.** Provide a final adjustment to simulation model by calculating the mean bias error (MBE)[1] and subtracting this amount from to the model so that the MBE of the model is zero for the baseline period. Even a small systematic bias in the simulation will decrease the sensitivity of the fault detection process.

5. **Program Regular Data Transfer to ABCAT.**

   Develop a method by which the required measured inputs can regularly be updated and passed to the ABCAT program. In the current test facilities, Visual Basic for Applications programs link the ABCAT with consumption data files. The programs sort, fill missing data with linear interpolation when applicable, summarize and import the data into the ABCAT program in its required format.

Once the ABCAT is configured for the particular building through the steps described above, the project is ready for execution. Figure 10 is a process flow diagram which visually describes the following five steps in the ABCAT methodology:

1. **Import Measured Data.**

   Evoke the project developed in step 5 of the initial setup steps above from the ABCAT program.

2. **Simulate Heating and Cooling Consumption.**

   The required inputs are passed to the energy simulation routine, where the heating and cooling consumption is simulated.

3. **Analyze Data.**

   The simulated consumption and measured consumption are passed to the data analysis routine that generates the building performance plots, compares and performs calculations on the two values, applies fault detection methods, and reports diagnostic and energy consumption statistics.

4. **Evaluate.**

   The user of the tool is to evaluate the data presented and determine whether or not a fault exists that requires action. The user plays an important role in defining fault triggers and manipulating the plotted data with easily adjustable parameters to suit their site specific preferences. One of the primary metrics established to aid in the user decision is the Cumulative Energy (or Cost) Difference plot, previously used by Haberl and Vajda (1988), which accumulates the energy residuals (difference between measured and simulated consumption) of persistent deviations from measured consumption by

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1. Defined as $MBE = \frac{\sum(E_{sim} - E_{meas})}{n}$ where n is the number of days in the calibration period.

adding them to that of the total of the previous day (multiplies the accumulated energy by a user specified utility cost for the Cost Difference plot). The cost plot presents the deviations in the universally understood language of dollars and cents, which is expected to help compel users of the ABCAT to act in the case of a fault.

5. **Take Action.**

   If action is deemed necessary, the type of action taken will depend on whether the faulty condition observed is the result of a required change in operations (where the simulation model must be recalibrated) or if it was caused by a system or component failure or a change in control to a less than optimal setting (where repair, maintenance or a control change may be in order). Diagnostic clues as to the origin of the fault can be provided by the described diagnostic methodology in the next section.

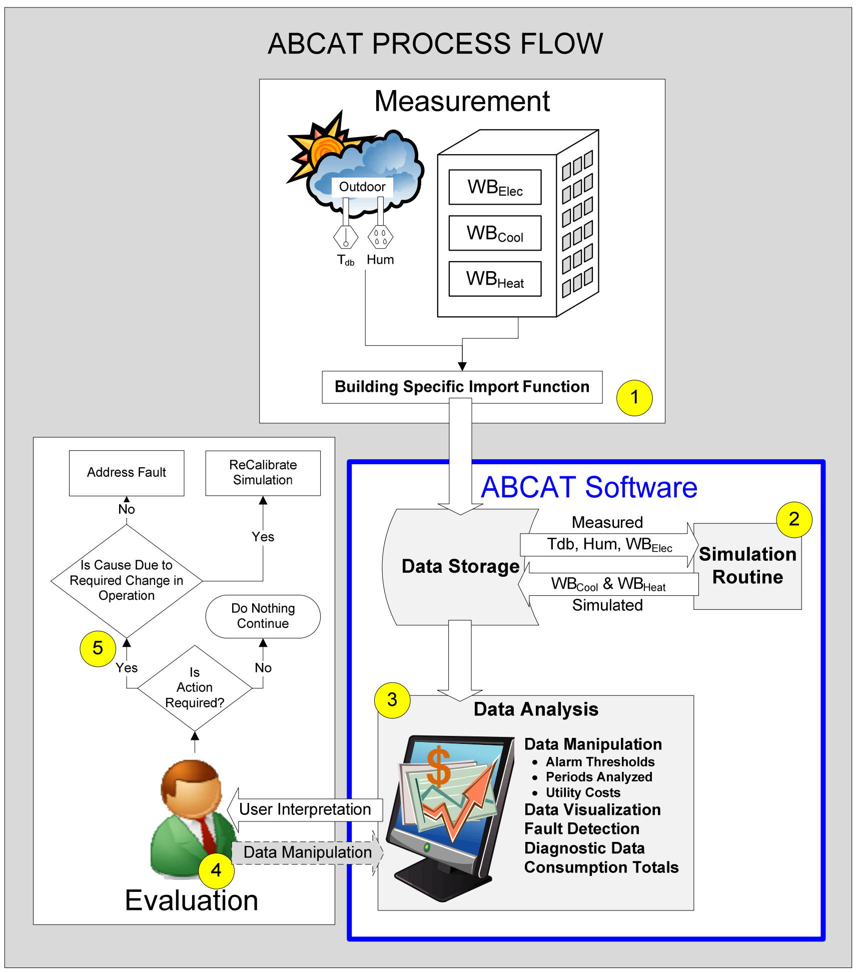

Figure 10. ABCAT Flow Diagram

Source: Portland Energy Conservation, Inc.

Simplified Diagnostic Methodology of the ABCAT

A diagnostic methodology for the ABCAT was developed that simply relates the heating and cooling residuals and the daily average outside air temperature and determines if the residuals are greater than ▲, less than ▼, or as expected ●. An example of this methodology is presented below for Single Duct Variable Air Volume (SDVAV) systems in Table 2. Each fault listed in Table 2 is divided into three temperature ranges based on ambient temperature: $T_{amb} < T_{SA,sp}$ (supply air temperature); $T_{SA,sp} \le T_{amb} \le T_{Econ,sp}$ (temperature the economizer deactivates); $T_{amb} > T_{Econ,sp}$. The gray shaded cells with the striped background represent faults that are expected to cause significant problems with comfort in the buildings, and are therefore more likely addressed with corrective measures before a significant and persisting energy impact will be observed by the ABCAT. Each fault listed can have several subcategories of more specific faults with similar symptoms. As data is gathered from more than one of the ambient temperature ranges, the possibilities for a more deterministic diagnosis improve.

Table 2. SDVAV w/Economizer Rules for Diagnostic Classifier

Fault Type		Higher			Lower		
		$T < T_{SA,sp}$	$T_{SA,sp} < T < T_{econ,sp}$	$T > T_{econ,sp}$	$T < T_{SA,sp}$	$T_{SA,sp} < T < T_{econ,sp}$	$T > T_{econ,sp}$
1. Supply Air Flow Rate	Cooling	Off	▲	▲	Off	▼	▼
	Heating	▲	▲	Off	▼	▼	Off
2. CHW Pump DP	Cooling	Off	▲	●	Off	▼	●
	Heating	N/A	▲	Off	N/A	▼	Off
3. HW Pump DP	Cooling	Off	▲	N/A	Off	●	N/A
	Heating	▲	▲	Off	▼	▼	Off
4. Outside Air Flow Rate							
a. Minimum OA Flowrate	Cooling	N/A	N/A	▲	N/A	N/A	▼
	Heating	N/A	N/A	Off	N/A	N/A	Off
b. Economizing OA Flowrate	Cooling	Off	N/A	N/A	Off	▲	N/A
	Heating	▲	N/A	N/A	▼	●	N/A
c. Economizer Temperature	Cooling	N/A	●	▲	N/A	▲	●
	Heating	N/A	●	Off	N/A	●	Off
5. Supply Air Temperature	Cooling	Off	▼	●	Off	▲	Same
	Heating	N/A	▼	Off	▲ or ●	▲	Off
6. Metering							
a. Chilled Water Meter	Cooling	Off	▲	▲	Off	▼	▼
	Heating	●	●	Off	●	●	Off
b. Hot Water Meter	Cooling	Off	●	●	Off	●	●
	Heating	▲	▲	Off	▼	▼	Off
7. Scheduling		Longer			Shorter		
a. Chiller	Cooling	▲	▲	▲	▼	▼	▼
	Heating	▲	▲	▲	▼	▼	▼
b. Boiler	Cooling	▲	▲	▲	▼	▼	▼
	Heating	▲	▲	▲	▼	▼	▼

Notes: N/A - Not Applicable; Cooling Off When $T <$ $_{SA,sp}$; Heating Off When $T >$ $_{econ,sp}$

4.2. Project Element Outcomes

ABCAT Layout

The ABCAT is laid out as any typical Microsoft Excel file, with multiple worksheets and chart sheets accessible by the colored tabs at the bottom of the screen. The Interface sheet is the gateway of communication between the user and the tool, and includes the following features:

- The dates of the periods analyzed can be adjusted.
- Various alarm thresholds can be modified to user preferred levels.

- Utility cost information can be specified.
- Folder and file locations can be setup for importing and saving data files.
- The calibrated simulation statistical results for the baseline.
- Consumption totals and diagnostic summary of the period analyzed.

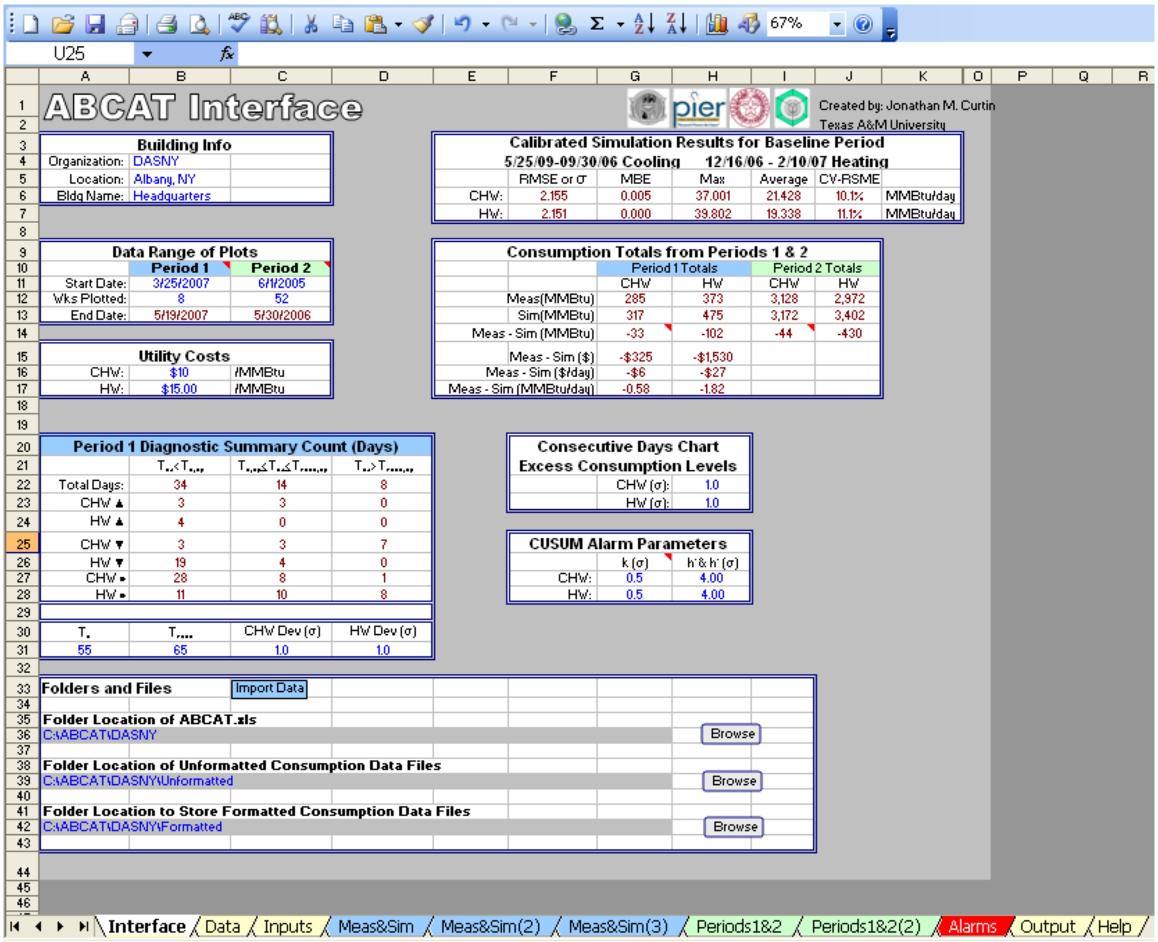

Figure 11. The ABCAT User Interface

Other features:

- Multiple plots on each of five chart sheets providing performance data comparing measured and simulated or two periods of measured data.
- Quick day-type and date association by double clicking on any plotted point.
- Capability to scroll through time with the scroll bars.
- Daily data summarized and stored in the tool such that the simulation can run for any period without user concern of reprocessing or collecting required inputs.

Analysis of Comments and Feedback

In the developmental process of the ABCAT, informal comments and feedback came from users, potential users, and management and advisory members involved in the project. Although no statistical significance can be assigned to this feedback due to the small number of participants involved and the absence of a formal collection methodology, this feedback has nonetheless been beneficial in implementing upgrades to the tool and setting the course for future developmental and testing steps.

Summary of New York Pilot Feedback

The pilot participants found the tool to be “very helpful and beneficial for tracking energy consumption on a higher level” and “good for both building owners and operators” although it was stated that the tool “cannot take the place of on-site diagnostics.” On weekly time intervals the required consumption data was imported into the tool, and it was perceived by one user that the optimal time interval for using the tool is weekly. Microsoft Excel as the host program was considered “Good” as far as file size, speed of execution, graphical capabilities, data storage general file layout, familiarity and ease of operation were concerned. A preference was expressed for greater clarity with labels on the Interface sheet for user manipulated fields, consumption period totals for both defined periods on the Interface sheet, and a linking to greater granularity (hourly) than daily data. One user expressed interest in a lesson to calibrate the tool.

Software Layout and Performance

With the use of Microsoft Excel as a host to the ABCAT, speed of execution, program flow and the size of the project were concerns although current performance capabilities were viewed as favorable. Recommendations for linking to Microsoft Access were made, which could strengthen data storage capabilities and allow for storage of smaller time interval and supporting data that would not be feasible to manage with Excel alone. The familiarity of most users with the general functionality of Excel was seen as a bonus.

As far as the graphical presentation of the tool was concerned, positive feedback was received from the multiple plots per chart sheet layout, scroll bars for zooming, and pop-up window feature for identifying day type and date of specific data points. The Interface sheet of the tool was upgraded in response to recommendations for including data summary tables, and ease of identifying user control options. Additional recommendations of including day typing, highlighting the most recent data on plots, and general “cleaning” of the plot areas were found to be valuable. Due to the variety of viewing preferences by user, options are provided in the ABCAT for rearranging the existing chart layout, or creating new plots altogether.

Interest in Continued Testing

Throughout the course of many presentations and discussions involving the tool, there has been interest expressed by NYSERDA for continued developmental and expanded testing in New

York, as well as a desire by two building owners overseas in the Netherlands and Germany to have the ABCAT installed in their buildings.

Live Test Cases

The ABCAT was implemented in four live building situations. Various levels of automation and file manipulation were built into a specific data collection process for each building based on its unique conditions regarding data availability and format. The testing of the ABCAT in the four buildings provided a live learning scenario that helped to influence continued developments, and a summary of these test cases is provided in Table 3. The energy deviations detected in Sbisa Dining Hall and the Computing Services Facility are particularly interesting, since they both were unexpected and went undetected by building personnel. The diagnosis of two of the three faults observed in these two buildings benefited from the diagnostic methodology described in Section 4.1, but also required some additional investigation, questioning of building personnel, and review of building automation system (BAS) trend data.

Table 3. Test Buildings, Results and Findings from Live ABCAT Implementation

Building Description	Location	Test Period	Results and Findings
82,000 ft^2 university dining facility	College Station, Texas	Mar 2005 – present	Detected excess cooling energy fault (Figure 12) related to excessive latent cooling from low discharge air temperature on 2 of 3 Outside Air Handling Units – Summer 2006. Magnitude of the detected difference was 16.5% greater than average annual consumption.
482,000 ft^2 computing services facility	Austin, Texas	May 2005 – present	Detected significant decrease in measured cooling energy (Figure 13) due to meter calibration – Oct 2005. Magnitude of the detected difference was 9.3% less than average annual consumption. A second fault, significant excess cooling energy (Figure 14) detected in Nov 2006 - no definitive diagnosis. Magnitude of the detected difference was 9.5% greater than average annual consumption. Demonstration of successful short-term adaptation of simulation to multiple baseline changes.
180,000 ft^2 office building	Albany, New York	Jan 2007 – present	Successful monitoring of heating energy savings (Figure 15) following implementation of RCx measures. Training and support for two ABCAT testers.

Building Description	Location	Test Period	Results and Findings
190,000 ft^2 high-rise office building	Omaha, Nebraska	Feb 2007 – present	Confirmation of optimal heating and cooling energy through continued tracking. Identification of hot water metering failure (Figure 16), and recovery

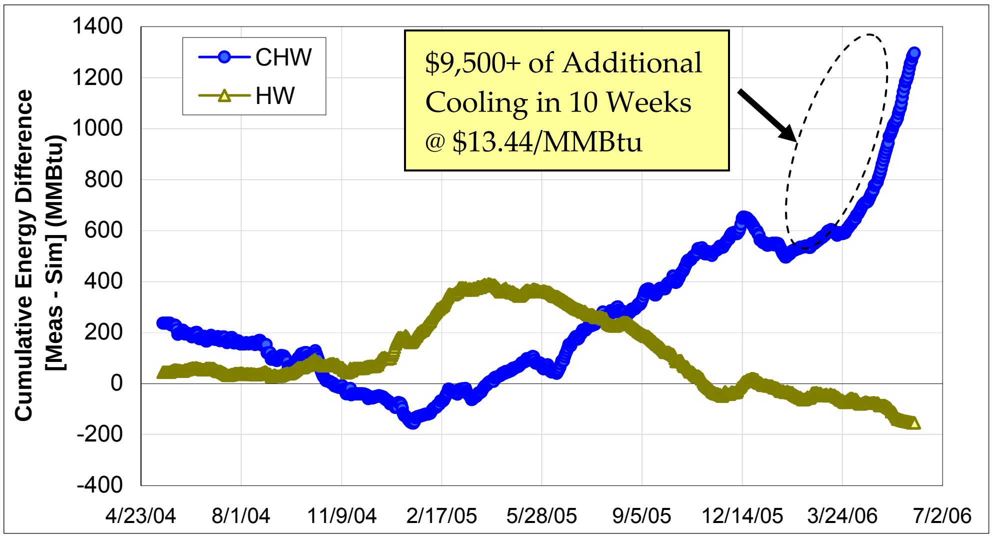

Figure 12. Sbisa Dining Hall Cumulative Energy Difference

Source: Portland Energy Conservation, Inc.

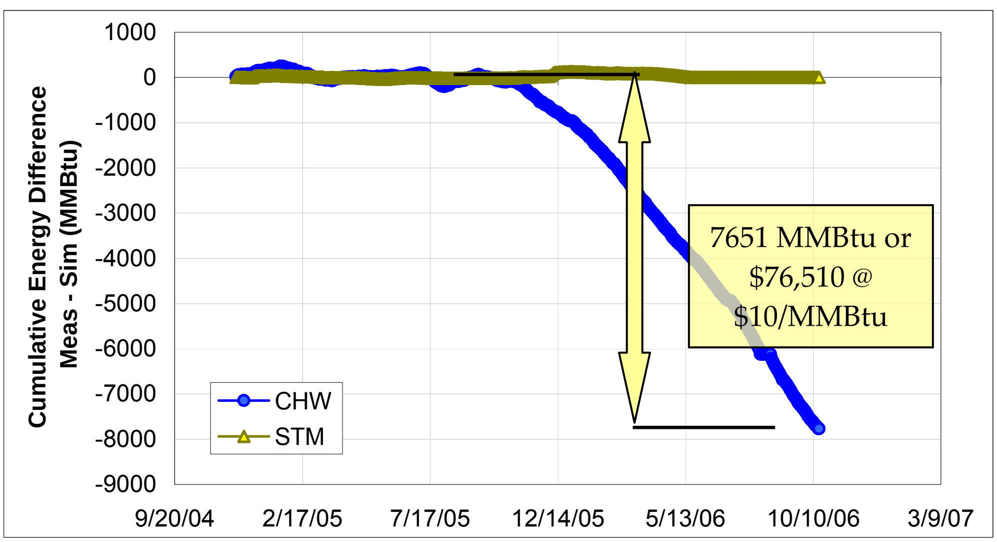

Figure 13. Computing Services Facility ABCAT Cumulative Energy Difference Meas – Sim (MMBtu) with Simulation Calibrated to Period of 12/01/2004 to 10/27/2005

Source: Portland Energy Conservation, Inc.

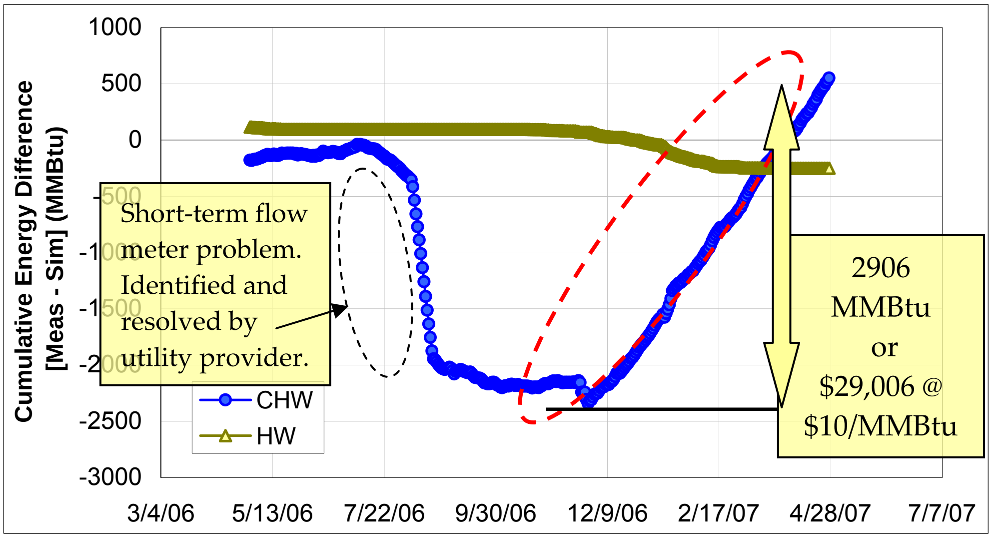

Figure 14. Computing Services Facility Cumulative Energy Difference for period starting 04/29/2006 for 1 year after simulation recalibrated to period of 10/27/2005 – 5/19/2006

Source: Portland Energy Conservation, Inc.

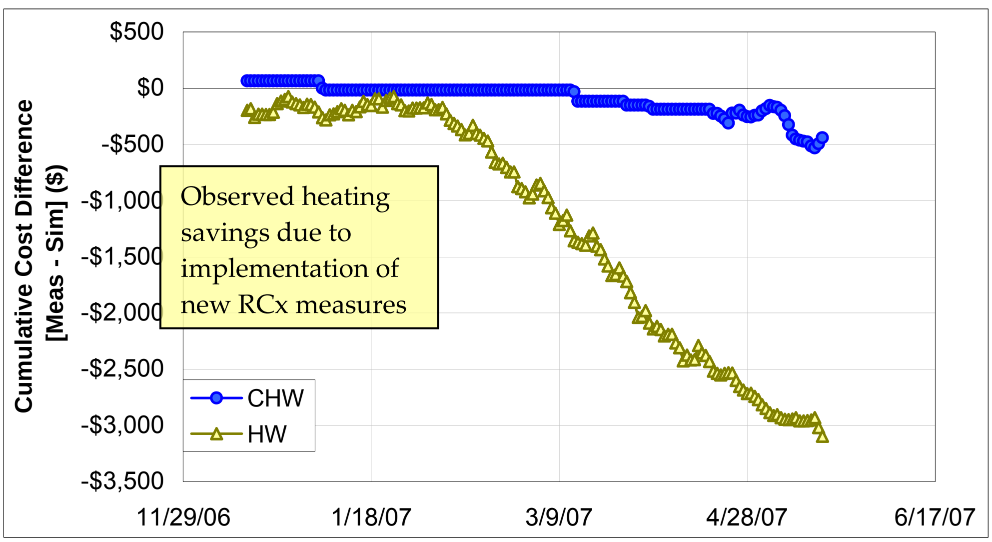

Figure 15. DASNY Cumulative Cost Difference ($15/MMBtu Heating, $10/MMBtu Cooling)

Source: Portland Energy Conservation, Inc.

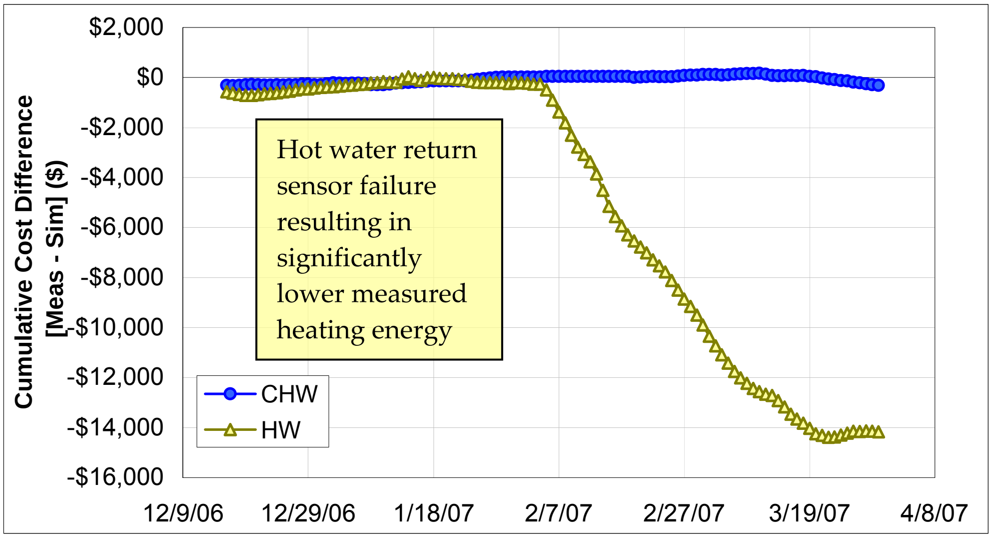

Figure 16. OPPD Energy Plaza Cumulative Cost Difference ($15/MMBtu Heating, $10/MMBtu Cooling)

Source: Portland Energy Conservation, Inc.

The testing of the ABCAT in these four buildings, the identification of the faults and the diagnostic reasoning that followed, helped shape the developmental direction of the ABCAT. Some of the keys points to take away from these early test experiences are the following:

- Whole building analysis can provide valuable diagnostic information.
- Accumulated deviations from optimal performance provide the best indicator of significant faults that persist and cost information.
- The value of ABCAT does not appear to lie in daily short-term observations, but rather in observations on the order of weeks to months.
- The advantage of using a first principles simulation model can be seen with occasional recalibrating requirements due to changes in building operations.

Retrospective Implementation in Five Texas Buildings

Although a second New York test facility was originally identified and targeted for installation of the ABCAT, difficulties in obtaining the required preliminary baseline consumption data prevented a successful deployment. A five building retrospective analysis was performed with ABCAT in lieu of a second New York building. These buildings are Harrington Tower, the Kleberg Center, Eller Oceanography-Meteorology Building, Veterinary Research Building and the Wehner Building on the Texas A&M University campus. A retrospective implementation of the ABCAT in five buildings was expected to provide additional testing of this diagnostic methodology, but instead primarily highlighted the importance of data quality.

There were 24 faults that were detected with deviations greater than +/- one standard deviation (as determined from the statistics of the calibrated simulation) that persisted for the period of at least one month. These faults, calculated as min, max, and median percentages of the average annual simulated consumption were 11.1 percent/107 percent/25.6 percent for the 13 CHW faults, and 39.0 percent/210 percent/106 percent for the 11 HW faults. The combination of incomplete metering data, suspect metering data, along with a lack of sufficient detailed performance knowledge surrounding the periods of the faults, prevented a successful application of the diagnostic methodology in these cases. Nonetheless, these retrospective tests provided an opportunity to test the simulation capabilities of the ABCAT in five additional buildings of varying type and function.

4.3. Conclusions and Recommendations

4.3.1. Conclusions

The ABCAT has been shown to be a valuable energy tracking tool, identifying three periods in the live building implementations where significant energy consumption changes occurred that otherwise went undetected by the building energy management personnel. In each of these cases it was the accumulation of daily differences between measured and simulated consumption that provided the clearest indication of the fault. The methodology applied also has shown that it is not prone to false positives, or false alarms. In long-term multi-year implementations, both in the real-time testing and retrospective analyses, the cumulative difference plot often simply verified that energy operations were well within acceptable limits for many extended periods.

The potential future success of the ABCAT is strongly tied to the ability of future users to obtain accurate and reliable measurements. A strong emphasis in sound engineering practices of installation, data management, calibration and data prescreening must accompany the ABCAT to ensure verification of data quality and the likelihood for success in implementing the tool.

In addition to the originally targeted goals of tracking and ensuring energy optimization in commissioned buildings, several other added benefits or alternative functional approaches have been identified through the course of implementing and testing the ABCAT. These include use of the ABCAT as a commissioning savings tracking tool, a simple whole building energy analysis tool (even without the simulated consumption), and a tool to provide verification of or filling of missing metered or billing data, both important for customers of district utility providers and potentially the providers themselves.

4.3.2. Recommendations

Real building testing of the ABCAT is an invaluable learning experience, and a larger scale (10+ buildings) implementation over the course of the next two years is recommended to identify further field user requirements and provide insight into the true marketability of the tool. Installing the ABCAT prior to commissioning activities in these buildings appears to be a good way of tracking savings due to commissioning measures, but also provides an opportunity to reverse test the developed diagnostic methodology of the tool. Training additional expert users of the tool and developing supporting software or tools and detailed documentation to simplify the calibration procedure are ways to begin to disseminate the tool among multiple users. This will result in an even greater level of detail and diversity in feedback which can be used for advanced development. An estimated funding level of $250,000 is likely required over a period of two years to complete this second phase of testing.

Several developmental issues should be addressed early in continued research, particularly in the areas of improving data transfer and storage and additional testing of the diagnostic methodology to determine if it can be viewed as sufficiently robust for incorporation in the ABCAT as an automated diagnostic method. The ABCAT also needs to be modified to incorporate suggestions from the limited field testing completed to date, to include instruction sets prepared to aid users in transmitting input data from several common data sources, and be reprogrammed and documented in accordance with standards for commercial software to produce a commercially viable product from the prototype ABCAT tool developed under the STAC project. An estimated funding level of $200,000 is likely required over a period of two years to complete the testing, software upgrades and documentation of the above described advanced developmental steps of the ABCAT.

4.3.3. Benefits to California and Other Participating States

The ABCAT has demonstrated on a small scale that it can bridge the gap in proactive energy management between the manual comparison of monthly energy bills and FDD tools for HVAC systems that are heavily reliant on sensors, expensive, require large training (historical) data, and are overly sophisticated for typical users.

The ABCAT identifies and displays the cost impact of significant (+5 percent) energy consumption faults in buildings that often go undetected or are not acted upon because the energy or cost significance is underestimated. With wide-scale deployment of an inexpensive, simplified tool such as the ABCAT to commissioning service providers, building owners or engineers, the long-term persistence of savings from building commissioning can be realized with continuous energy tracking. The ABCAT may also aid in the promotion of building commissioning services by presenting building owners with a tool to monitor continued savings. The results of this project lay the foundation for extending the energy benefits of building commission such that states can meet their goals for energy conservation and optimization in buildings. Continued testing and development of the ABCAT will be required before these large scale goals can be accomplished.

Chapter 5.0 References

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Chapter 6.0 Glossary

ABCAT	Automated Building Commissioning Analysis Tool
ASHRAE	American Society of Heating, Refrigeration and Air Conditioning Engineers
BAS	Building Automation Systems
CHW	Chilled Water or Chilled Water (cooling) energy consumption
Cx	New Building Commissioning
DASNY	Dorm Authority of the State of New York
DDCV	Dual Duct Constant Volume
DDVAV	Dual Duct Variable Air Volume
DFDDVAV	Dual Fan Dual Duct Variable Air Volume
FDD	Fault Detection and Diagnostics
HVAC	Heating Ventilating and Air Conditioning
HW	Hot Water or Hot Water (heating) energy consumption
MBE	Mean Bias Error
RCx	Retrocommissioning
SDCV	Single Duct Constant Volume
SDVAV	Single Duct Variable Air Volume
SEAP	Simplified Energy Analysis Procedure
SZHC	Single Zone Heating and Cooling
VAV	Variable Air Volume
WB_{Cool}	Whole Building Cooling
WB_{Heat}	Whole Building Heating